

**RECOGNITION OF MILANKOVITCH ORBITAL FORCING
PATTERNS IN SHELF FACIES OF THE LOWER DEVONIAN
NEW CREEK AND CORRIGANVILLE FORMATION OF
CENTRAL PENNSYLVANIA**

A Thesis Submitted
to the Temple University Graduate Board

in Partial Fulfillment
of the Requirement for the Degree

MASTER OF ARTS

by

Christopher Orzechowski

August 1995

DEPARTMENT COPY

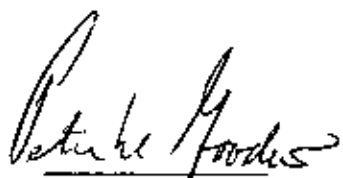
RECOGNITION OF MILANKOVITCH ORBITAL FORCING PATTERNS
IN SHELF FACIES OF THE LOWER DEVONIAN
NEW CREEK AND CORRIGANVILLE FORMATIONS
OF
CENTRAL PENNSYLVANIA

A Thesis
Submitted to
the Temple University Graduate Board

in Partial Fulfillment
of the Requirements for the Degree
MASTER OF ARTS IN GEOLOGY

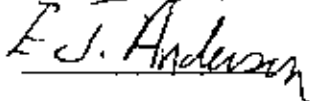
by

Christopher Orzechowski

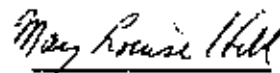


Thesis Advisor

August, 1995



Committee Member



Committee Member

ABSTRACT

Application of the Milankovitch model of allocyclicality to the New Creek and Corriganville Formations in central Pennsylvania reveals vertically consistent and laterally correlative stacking patterns of fifth-order and sixth-order cycles in below-wave-base shelf facies. Overlying an unconformable third-order sequence boundary (Keyser-New Creek boundary), the formational succession consists of progressively deeper fifth-order sequences traceable throughout Pennsylvania. The New Creek Formation is one fifth-order sequence, consisting of shallow-shelf, bioturbated calcarenite packaged into three meter-scale allocycle or (PACs). This fifth-order sequence, incomplete because of hiatus at the third-order boundary, is asymmetric, shallowing to peritidal facies in the uppermost Pac at Tyrone. In general, the Corriganville Formation is a complete fifth-order sequence consisting of five sixth-order cycles, but is incomplete at Tyrone where the basal PAC is missing. PAC 1 was not deposited at Tyrone because this area was not flooded by the first precessional rise in the Corriganville fifth-order sequence. Unlike New Creek PACs, which are internally gradational, Corriganville PACs contain distinct highstand and lowstand portions separated by a sea-level-fall surface. Precession-driven eustasy is responsible for the primary cyclic fabric of this stratigraphic interval. Eccentricity functioned as a modulator by enhancing the precessional affect at the fifth-order boundaries and by dampening the precessional affect within the fifth-order sequence and producing a general shallowing-upward trend. Recognition of these cyclic patterns, at the sixth and fifth-order scale, lends support to the concept of a genetic hierarchy of allocycles.

ACKNOWLEDGMENTS

I would like to thank Dr. Peter Goodwin for all his help, encouragement and support during my time at Temple. Pete not only stimulated my academic growth but encouraged my development as an individual and I think of Pete not only as mentor but as a friend.

In addition, I would like to thank Dr. Anderson and Dr. Hill for their critical review of this paper and support during my studies, as well as the Temple University Geology Department.

I would like to thank my parents Richard and Lillian for their love and foundation during all of my academic pursuits. Also I would like to thank Bob and Carolyn Eckel for the wonderful encouragement while attending graduate school.

Most of all, I would like to thank my wife Suzanne Eckel for all her love and seemingly endless patience over the past five years and her inner strength which provided me with the determination to complete my undertaking, I thank you my love.

TABLE OF CONTENTS

	Page
ABSTRACT	ii
ACKNOWLEDGMENTS	iii
LIST OF FIGURES	vi
 CHAPTER	
1. INTRODUCTION	1
Purpose	1
Objectives	2
Methods	2
2. STRATIGRAPHIC MODELS	4
Punctuated Aggradational Cycles	4
Milankovitch Orbital Forcing Patterns	11
Genetic Hierarchy of Allocycles	16
3. CYCLICITY IN THE NEW CREEK AND CORRIGANVILLE FORMATION	23
Stratigraphic Setting	23
Sixth-Order Cycles (PACs)	26
New Creek Sixth-Order Cycles	27
Corriganville Sixth-Order Cycles	37

Fifth-Order Sequences	51
New Creek Fifth-Order Sequence	51
Corriganville Fifth-Order Sequence	54
4. SUMMARY AND CONCLUSIONS	57
REFERENCES CITED	59

LIST OF FIGURES

	Page
Figure 1. The PAC Model	5
Figure 2. Gradualistic Interpretation of the Helderberg Group.. ..	7
Figure 3. The Precessional Signal	13
Figure 4. The Eccentricity Mechanism	15
Figure 5. The Sequence Stratigraphy Hierarchy.	18
Figure 6. A Process-Determined Stratigraphic Hierarchy.	21
Figure 7. Lower Devonian Outcrop in Pennsylvania	24
Figure 8. Genralized Stratigraphic Column, Central Appalachians	25
Figure 9. Symbols for Stratigraphic Columns.	30
Figure 10 The New Creek Fifth-Order Sequence at Altoona Bypass.	31
Figure 11. The New Creek Fifth-Order Sequence at Canoe Creek.	32
Figure 12. The New Creek Fifth-Order Sequece at Tyrone	33
Figure 13. The New Creek Fifth-Order Sequence at Cessna.	34
Figure 14. The New Creek Fifth-Order Sequence at Hollidaysburg.	36
Figure 15. The Corriganville Fifth-Order Sequence at Hollidaysburg.	38
Figure 16. Typical Corriganville Sixth-Order Cycle, PACs 4 and 5 at Hollidaysburg. .	40
Figure 17. The Corriganville Fifth-Order Sequence at Hollidaysburg.	42
Figure 18. The Corriganville Fifth-Order Sequence atCanoe Creek.	43
Figure 19. The Corriganville Fifth-Order Sequence at Tyrone.	44

Figure 20. PACs 3 and 4 at Canoe Creek.	48
Figure 21. PAC 3 at Hollidaysburg.	49
Figure 22. The Corriganville Fifth-Order Sequence at Cessna.	50
Figure 23. Eustacy in the 100 k.y. Eccentricity Signal.	52
Figure 24. The Corriganville Fifth-Order Sequence at Tyrone.	56

CHAPTER 1

INTRODUCTION

Purpose

The primary purpose of this thesis is to describe and correlate small-scale cycles of shelf facies in the New Creek and Corriganville Formations of Central Pennsylvania. Recognition and interpretation of allocycles in the stratigraphic record and the evaluation of the mechanisms responsible for their formation have been the subjects of a number of studies in recent years. These fundamental investigations include: Cambrian-Ordovician carbonates (Koerschner and Read, 1990; Read and Goldhammer, 1988; Oselger and Read, 1991), Upper Silurian-Lower Devonian peritidal-subtidal carbonates (Goodwin and Anderson, 1985), Pennsylvanian cyclothems (Busch and Rollins, 1984), Mississippian ramp to deep slope carbonates (Erick and Read, 1991), Middle Triassic platform carbonates (Goldhammer, Dunn and Hardie, 1987), Jurassic Cretaceous carbonates (Strasser, 1994) and Cretaceous pelagic sediments (Fischer and Bottjer, 1991; Fischer et al., 1991). Very few of these studies document allocycles in carbonate shelf environments. Even in the case of Goodwin and Anderson's (1985) Punctuated Aggradational Cycles (PACs) model, which argues that allocyclicality exists in all facies influenced by changes in base-level, most of the direct field testing of the model has been in shallow near-shore to peritidal carbonate facies. This study will apply the PAC model in the analysis of cyclicity in deeper carbonate shelf facies.

Many studies of ancient allocycles have suggested Milankovitch-band orbital forcing mechanisms (e.g. Fischer, 1964; Goodwin and Anderson, 1985; Goldhammer, Dunn and Hardie, 1987; Fischer et al., 1991). However, there is a scarcity of studies clearly discriminating the effects of each orbital parameter (e.g. precession and eccentricity). It is the intent of this study to compare the cyclic patterns of the New Creek and Corriganville allocycles with the predictions of a hierarchic Milankovitch model with the purpose of distinguishing the effects of the common orbital forcing mechanisms.

Objectives

The specific objectives of this study are to: 1) establish criteria for recognizing meter-scale allocycles or PACs in open and deep shelf facies, of the New Creek and Corriganville Formations; 2) demonstrate correlations of PACs and their bounding surfaces throughout Central Pennsylvania; and 3) compare the stacking patterns of cycles, as defined by degree of facies change, with the predictions of the hierarchic Milankovitch model.

Methods

This study employed both field and laboratory techniques to interpret and collect data. Utilizing the PAC model, stratigraphic columns were constructed at eight localities along the Helderberg outcrop belt in central Pennsylvania. Cycle boundaries, stratigraphic surfaces, facies changes, sedimentary structures, fossil content, and textures were recorded at a scale of two feet to the inch. Thin-sections were prepared from polished slabs of samples taken above and below cycle boundaries to recognize the degree of facies change and to compare

textures of correlated cycles at different localities. Microscopic evaluation of the rock allowed for further detailed analysis of the lithology, texture and fossil content of the rock.

CHAPTER 2

STRATIGRAPHIC MODEL

Punctuated Aggradational Cycles

The Punctuated Aggradational Cycle (PAC) hypothesis is a comprehensive model that suggests that the stratigraphic record consists of meter-scale allocycles or PACs. The concept behind the PAC model (Goodwin and Anderson, 1985) is that stratigraphic accumulation is episodic, contradicting earlier stratigraphic models that employed a gradualistic concept of accumulation of sedimentary rock units (Fig. 1). From the perspective of PACs, a stratigraphic cycle is initiated by a geologically instantaneous rise in sea level. This rise in sea level is sufficiently rapid to disrupt deposition and produce a non-depositional surface. As the rise in sea level stabilizes, aggradation ensues until another abrupt rise in sea level produces another surface of non-deposition or discontinuity. These surfaces of non-deposition are traceable basin-wide (Goodwin and Anderson, 1985). Within the confines of these boundaries facies change is generally gradational, but disjunct facies relationships have been observed. This allogenic perspective contradicts traditional models and ideas of stratigraphic accumulation.

In the past, stratigraphers utilized large-scale formations and members as fundamental time-stratigraphic units. Each formation and member represented the migration of a single paleoenvironment in response to gradual changes in sea level.

PRECESSIONAL EUSTASY

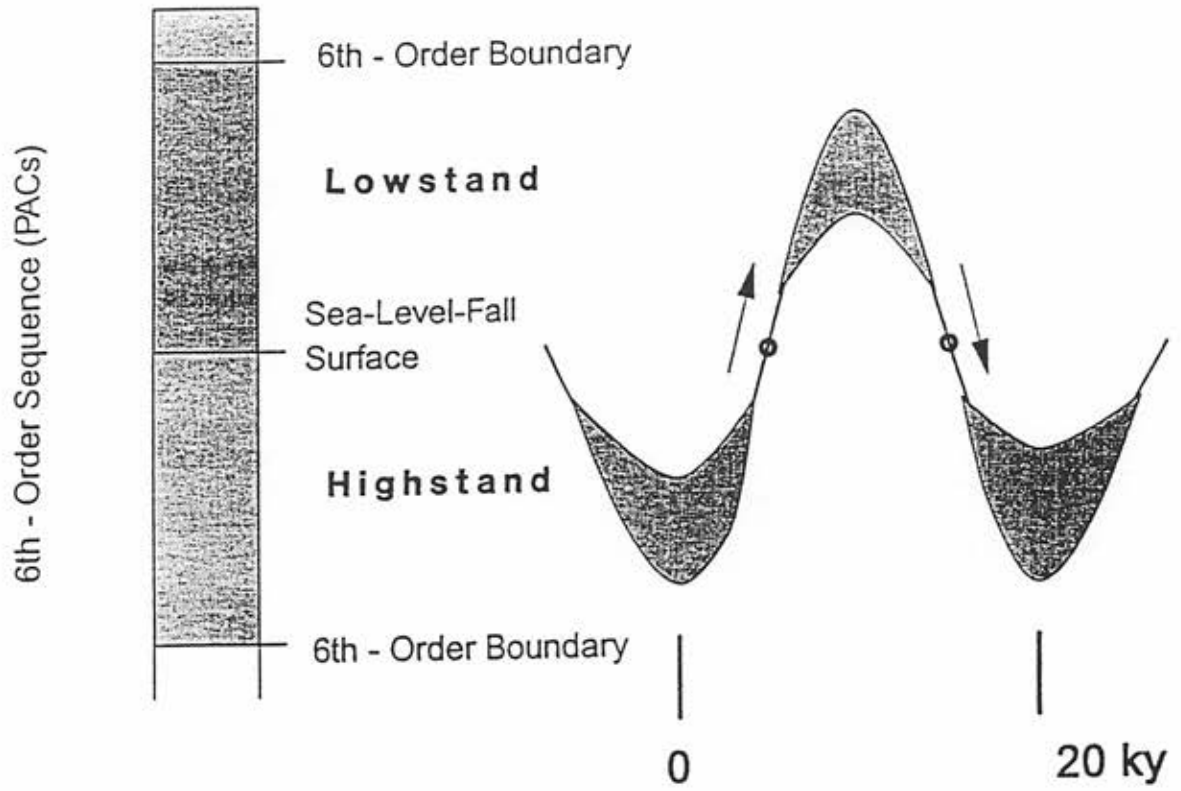


Figure 1. The PAC Model (From Goodwin and Anderson, 1985)

This gradualistic concept was challenged in the fundamental application of the PAC model to the Helderberg Group of New York State (Anderson et al., 1984, Goodwin and Anderson, 1985).

The Upper Silurian-Lower Devonian Helderberg Group of New York State was originally interpreted by Rickard (1962) and reinterpreted by Laporte (1969) utilizing gradualistic assumptions. From a gradualistic perspective, Laporte (1969) interpreted the Manlius-Coeymans-Kalkberg-New Scotland vertical sequence of formations in the Hudson Valley as representing a once contemporaneous set of paleoenvironments. This vertical succession of rock was interpreted as the result of lateral migration of large-scale facies belts in response to gradual sea-level rise or basin subsidence (Fig. 2). This stratigraphic approach, using the formation as the fundamental stratigraphic unit, implies that all intra-formational patterns should support the upward-deepening trend. Cyclicity and shallowing trends were dismissed as products of a local environmental mosaic, produced by autogenic processes (Laporte, 1969). Goodwin, Anderson and their students, of Temple University, recognized patterns of facies and facies changes in the Manlius Formation which did not support Laporte's hypothesis and reinterpreted the Manlius and the Helderberg Group using the PAC model (Goodwin et al., 1986; Goodwin and Anderson, 1988).

In these studies, Goodwin, Anderson and their students recorded correlative shallowing-upward patterns of facies (PACs) bounded by distinct surfaces of discontinuity in the Manlius Formation. They observed that these discontinuities juxtaposed deeper facies over shallower facies at the meter scale.

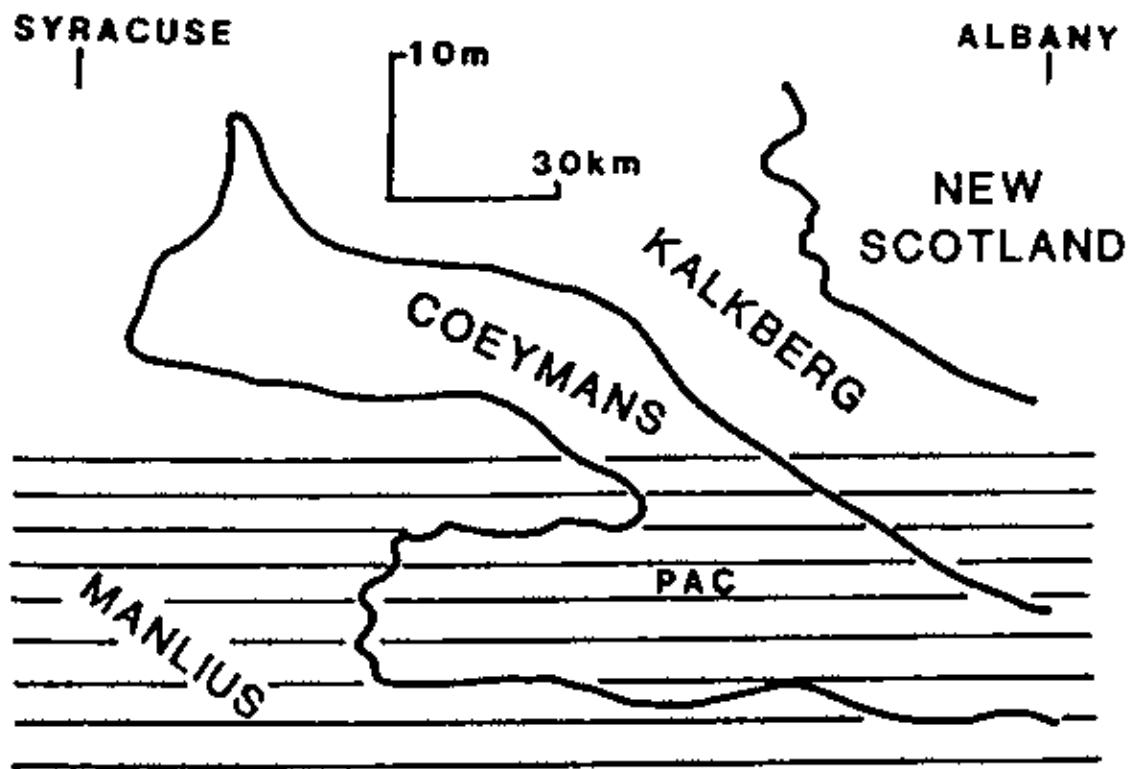


Figure 2. Gradualistic Interpretation of the Helderberg Group (From Laporte, 1969).

Utilizing these distinct features and a large number of closely spaced localities, correlations of cycles across the Helderberg Basin were established by tracing unique facies and patterns of facies changes and by matching major discontinuities (Goodwin et al., 1986). These observations and detailed correlations showed that the formations in the Helderberg Group did not form as a result of gradual basin-wide transgression but formed as a result of numerous episodic changes in sea level. Consequently, the PAC model placed all of the facies represented in the Manlius and the other formations in the Helderberg Group into a coherent framework of time-stratigraphic cycles and synchronous surfaces which contradicted Laporte's (1969) gradualistic interpretation (Fig. 2). Since this fundamental study, a great deal of work has been conducted in recognizing allocycles in the stratigraphic record.

Meter-scale allocycles have been recognized in Cambro-Ordovician peritidal carbonates (Koerschner and Read, 1989; Goldhammer and Read, 1988), Cambrian platform carbonates (Osleger and Read, 1991), Silurian marine-non-marine sediments (Mauriello and Ketterer, 1993; Shelton and Anderson, 1993), Silurian peritidal carbonates (Smith and Anderson, 1992; Chadwick and Goodwin, 1993), Pennsylvanian cyclothems (Busch and Rollins, 1984), Mississippian ramp to deep slope carbonates (Elrick and Read, 1991), Middle Triassic platform carbonates (Goldhammer, Dunn and Hardie, 1987) and Albian pelagic rhythmites (Fischer et al., 1991).

In their study, Read and Goldhammer (1988) recognized repetitive facies patterns which had sharp bases overlain by subtidal facies grading up into intertidal to supratidal facies. This pattern is similar to the PACs recognized by Goodwin, Anderson and their students in similar facies in New York and Pennsylvania. The sharp base in the PAC model would be

called a cycle boundary or discontinuity and the gradation from subtidal to intertidal would be recognized as the shallowing-upward motif. The model employed by Read and Goldhammer (1988) in their peritidal study requires that each cycle contain both a subtidal and an intertidal component. Consequently cycle boundaries are defined only where intertidal are supratidal facies were immediately overlain by a subtidal facies. Goodwin and Anderson (1985 and 1988) have demonstrated, in the Manlius Formation of New York and in the Keyser Formation of Pennsylvania, completely subtidal meter-scale allocycles associated with peritidal facies which were documented to be laterally extensive over tens of kilometers. These studies illustrate that the PAC model is not lithologically dependent because it examines disjunct facies patterns that formed in subtidal as well as peritidal environments.

Most allocyclic work to date has concentrated on the facies of shallow carbonate environments; little attention has been paid to deeper shelf, ramp and basin facies. Elrick and Read (1991) recognized allocycles in facies ranging from peritidal to basinal. The study focused on the recognition of shallowing-upward allocycles in Mississippian peritidal to shelf carbonates in Wyoming and Montana. The peritidal allocycles were recognized as subtidal facies capped by cryptalgal laminites and paleosols, a pattern similar to that of characteristic Cambro-Ordovician peritidal cycles (Read and Goldhammer, 1988). The subtidal facies were upward-fining indicating an overall shallowing-upward motif. Deep subtidal cycles were characterized by rhythmic repetition of limestone-argillite and capping skeletal grainstone (Elrick and Read, 1991). The upward-shallowing trends in the deep-subtidal cycles were interpreted from up-section increase in grain size, bed thickness, storm generated features, bioturbation, skeletal content and biotic diversity (Elrick and Read, 1991). Using these

characteristics Elrick and Read (1991) were able to recognize allocycles on the scale of 1-10 meters but did not show evidence of correlation at this scale. Correlations were established in this study at the scale of tens of meters by grouping the smaller-scale allocycles into larger sequences.

However, Side (1987) recognized and correlated meter-scale allocycles by applying the PAC model in similar deep shelf facies of the New Scotland Formation in New York State. Side (1987) stated that the Lower New Scotland Formation is completely divisible into 10 deep shelf PACs and that these PACs are traceable over an outcrop extent of 50 miles. The Lower New Scotland PACs are characterized by black shale abruptly overlain by beds of limestone, a pattern which is similar to the deep subtidal cycles recognized by Elrick and Read (1991). The distinct limestone-shale couplets were laterally extensive, suggesting that these deep water PACs formed in response to allogenic processes.

Over the past decade the PAC model has evolved. PACs were originally defined as one to five meters in thickness but recent work by Goodwin, Anderson and their students has found the typical PAC to be a meter or less in thickness. In addition to the disjunct facies relationship at PAC boundaries, recent studies (Touchberry et al., 1991; Orzechowski et al., 1992; Smith and Anderson, 1992; Chadwick and Goodwin, 1993) have documented sharp sea-level-fall surfaces internal to PACs. Both the bounding surfaces and the internal sea-level-fall surfaces are now thought to be the product of precessional eustasy (Fig. 1).

Milankovitch Orbital Forcing Patterns

Recently, much attention has been paid to the relationship between orbital perturbations and fluctuations in global sea level and ultimately the formation of allocycles (Goodwin and Anderson, 1985; Anderson and Goodwin, 1990; Bond et al., 1991; Brett and Baird, 1986; Elrick and Read, 1991; Osleger and Read, 1991; Fischer and Herbert, 1991; Strasser, 1994). Degree of eccentricity in the Earth's orbit around the sun and the wobble in its axis (precession) are recognized as the principal contributors to global sea level change. These perturbations, which occur in a predictable cyclic patterns, have been termed Milankovitch orbital forcing mechanisms.

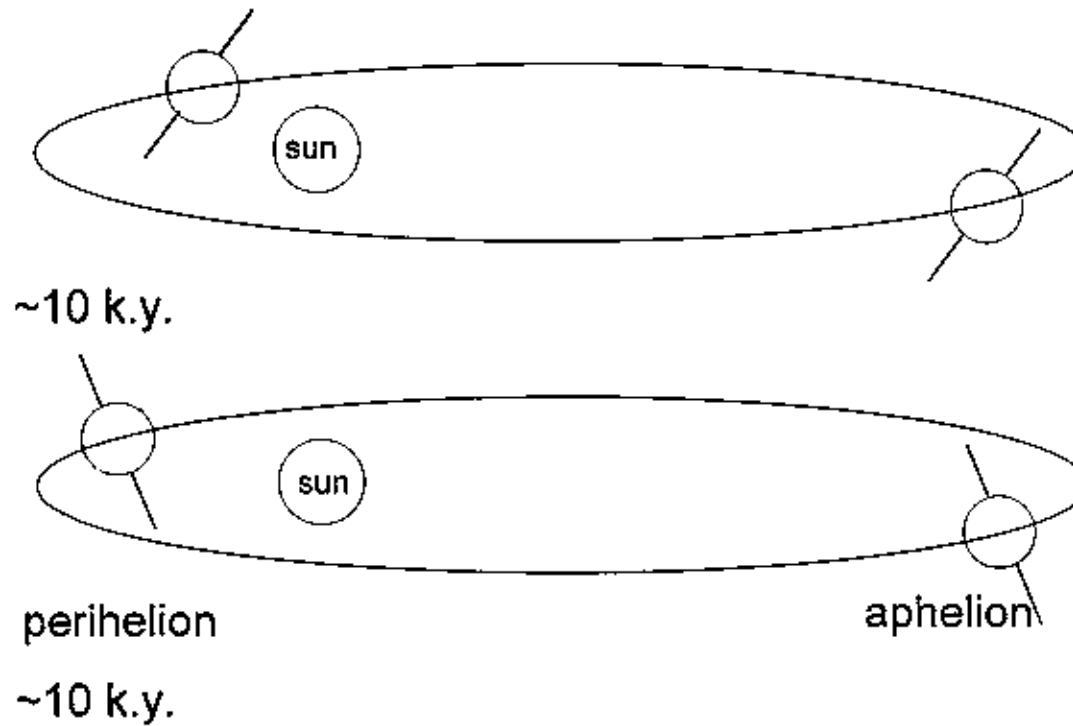
Milutin Milankovitch was a Yugoslavian astronomer whose main contribution was the exploration of solar insolation at different latitudes and seasons in great mathematical detail (Berger, 1988). From these data, Milankovitch computed tabulations and charts of northern hemisphere solar insolation and related these to planetary heat balance as determined by the planetary albedo and by reradiation (Berger, 1988). Essentially, Milankovitch compiled data on how much heat the Earth was receiving and reflecting into the atmosphere and how it varied seasonally and with latitude.

The connection between variation in solar insolation and sea level fluctuations requires that the summer in northern high latitude be cold enough to prevent the winter snow from melting, so as to allow a positive value in the annual budget of snow and ice, and to initiate a positive feedback cooling over the Earth through further extension of the snow cover and subsequent increase of the surface albedo (Berger, 1988). This condition would result in the majority of the Sun's heat being reflected into the atmosphere causing a decline of global

temperatures, additional ice build-up and ultimately a lowering of global sea level. These changes in the annual heat budget of the Earth from positive to negative and back in a geologic time frame would be reflected as fluctuations in global sea level.

Variations in the Earth's heat budget are produced by cyclic orbital perturbations. The two orbital perturbations include: 1) precession which describes the wobble in the Earth's axis and 2) eccentricity which addresses the ellipticity of the Earth's orbit about the Sun. Precession changes the direction of tilt in the Earth's axis and thereby the amount of solar insolation received by the northern hemisphere because of the progressive change in position of the summer solstice on the Earth's orbit. When the Earth's orbit is eccentric, the amount of solar insolation received by the Earth is dependant on the distance from the sun at the summer solstice in the northern hemisphere. Today, the summer solstice in the northern hemisphere occurs when the Earth is near aphelion resulting in a series of relatively cool summers in the northern hemisphere (Fig. 3). During the northern hemisphere's winter solstice, the Earth is at perihelion and the relative amount of solar insolation received by the southern hemisphere is high (Fig. 3). The direction of tilt in the Earth's axis changes like the wobble of a spinning top. This wobble or precession alters the amount of solar insolation received by either hemisphere as the solstices precess around the elliptical orbit of the Earth. Specifically, if the Earth's axis was tilted in such a manner that the northern hemisphere reached the summer solstice at perihelion, a negative ice budget would occur and glacial ice would melt producing a rise in global sea level.

The Precessional Signal



13

Figure 3. The Precessional Signal

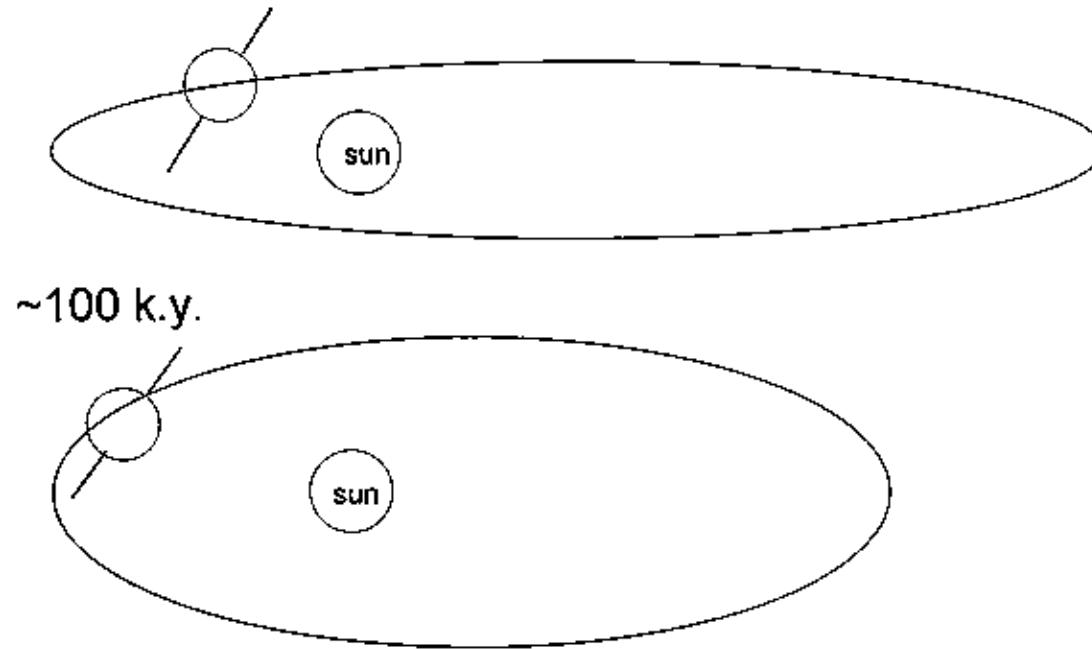
The clockwise polar-axis precession and counter-clockwise perihelion position interact to produce climatic effects.

On the other hand, if the Earth's axis was tilted so that the summer solstice occurred at aphelion, global sea levels would drop because of a positive ice budget. It should be noted that a complete precession cycle is the amount of time for the Earth's axis to return to its original position which is on the order of twenty-thousand years. Furthermore, the amount of rise or fall in global sea level would be modulated by the absolute proximity of the Earth to the Sun which is controlled by degree of eccentricity.

The Earth's revolution about the sun was first described by Keppler who observed the path to be elliptical. The ellipticity, however, changes over one hundred-thousand years from a more elliptical to a more circular path and back (Fig. 4). This variation in symmetry is important because during the time when the Earth's orbit is more circular, seasonality is more equal and at maximum ellipticity the largest change in degree of seasonality would occur (Fig. 4). Therefore, the largest annual negative ice budget would occur when the northern hemisphere is tilted towards the sun at perihelion at maximum ellipticity at which time the Earth would be closest to the Sun. In this configuration, a large rise in global sea level would occur. These variations in the precession and eccentricity cycles have regular predictable periods over a span of millions of years.

Precession and eccentricity may be the two major mechanisms responsible for fluctuations in global sea level. The precessional cycle currently has a period of 26 k.y. but what concerns this study is its period relative to the elliptical orbit which, due to the rotation of the orbit, varies between extremes of about 14 k.y. and 28 k.y. , with modes at ca. 19 k.y. and 23 k.y. (Fischer and Bottjer, 1991). Therefore, the average period of the precessional cycle is approximately 20 k.y. which translates in to a positive heat budget. The eccentricity

Eccentricity



15

Figure 4. The Eccentricity Mechanism

Precession is the primary mechanism that controls sea-level fluctuations. Eccentricity of the Earth's orbit around the Sun enhances or dampens the precessional effect.

include one major cycle (with various subsidiary components) The eccentricity cycles include one major cycle (with various subsidiary components) centered around 100 k.y. and another at about 400 k.y. (Fischer and Bottjer, 1991). Periodic variations in eccentricity produce two discrete levels of precessionally driven sea-level fluctuations in a hierarchic arrangement of cycles. These cyclic fluctuations in sea level are exhibited as hierarchically grouped sets of meter-scale allocycles or PACs separated by stratigraphic surfaces in the geologic record.

Genetic Hierarchy of Allocycles

Over the years, stratigraphers and sedimentologists have observed a hierarchic arrangement of allocycles in the stratigraphic record (e.g. Vail et al., 1977; Busch and Rollins, 1984). Attempts to explain this hierarchic structure resulted in placing apparently natural groups of allocyclic units into large compartments of geologic time with no specific process or duration connected to ranks in the hierarchy. More recently, stratigraphers attempted to integrate the generally accepted Milankovitch orbital forcing mechanisms with this hierarchic structure (Fischer and Herbert, 1986; Anderson and Goodwin, 1990; Strasser, 1994; Oselger and Read, 1991; Crevello, 1991). However, there are numerous opinions on which mechanisms are responsible for each level of cyclicity and how a hierarchy should be constructed.

In their fundamental study of sequence stratigraphy, Vail et al. (1977) established a stratigraphic hierarchy through the sub-division of large-scale unconformity-bounded sequences following the basic concept of Sloss (1963). In the sequence stratigraphy hierarchy (Fig. 5), the fundamental unit is the depositional sequence which is defined as a relatively conformable succession of In the sequence stratigraphy hierarchy (Fig. 5), the fundamental unit is the depositional sequence which is defined as a relatively conformable succession of genetically related strata bounded by unconformities and their correlative conformities (Van Wagoner et al., 1990). The depositional sequence ranges in thickness from 50 to over 1000 feet and has a duration of 100 k.y. to 1 m.y. Depositional sequences consist of parasequences and parasequence sets defined by major marine flooding surfaces and their correlative surfaces. The parasequence set ranges in thickness from 50 to 500 feet, and has a duration of 10 k.y. to 100 k.y. Parasequence sets are divided into parasequences defined as a conformable succession of genetically related beds or bedsets bounded by marine flooding surfaces and their correlative surfaces (Van Wagoner et al., 1990). A parasequence, like other components of sequence stratigraphy, has no definitive duration or thickness but averages 10 to 120 feet and has a duration of 1 k.y. to 100 k.y. (Van Wagoner et al., 1990). Thus the components of sequence stratigraphy are arranged in a non-genetic hierarchy consisting of orders defined by exponential divisions of geologic time. However more recent studies have attempted to establish links between a hierarchy of allocycles and specific orbital forcing mechanisms.

STRATAL UNITS	DEFINITIONS	RANGE OF THICKNESSES (FEET)				RANGE OF LATERAL EXTENTS (SQ. MILES)				RANGE OF TIMES FOR FORMATION (YEARS)				TOOL RESOLUTION				
		1000	100	10	1	10,000	1000	100	10	1	10 ⁵	10 ³	10 ⁴	10 ²	10	1	PALEO	EXPLORATION SEISMIC
SEQUENCE	A RELATIVELY CONFORMABLE SUCCESSION OF GENETICALLY RELATED STRATA BOUNDED BY UNCONFORMITIES AND THEIR CORRELATIVE CONFORMITIES (MITCHUM AND OTHERS, 1977)	[Shaded box from 1000 to 100]				[Shaded box from 10,000 to 1000]				[Shaded box from 10 ⁵ to 10 ³]				[Shaded bar from PALEO to EXPLORATION SEISMIC]				
PARA-SEQUENCE SET	A SUCCESSION OF GENETICALLY RELATED PARASEQUENCES FORMING A DISTINCTIVE STACKING PATTERN AND COMMONLY BOUNDED BY MAJOR MARINE-FLOODING SURFACES AND THEIR CORRELATIVE SURFACES.	[Shaded box from 100 to 10]				[Shaded box from 1000 to 100]				[Shaded box from 10 ⁴ to 10 ²]				[Shaded bar from EXPLORATION SEISMIC to WELL LOG]				
PARA-SEQUENCE	A RELATIVELY CONFORMABLE SUCCESSION OF GENETICALLY RELATED BEDS OR BEDSETS BOUNDED BY MARINE-FLOODING SURFACES AND THEIR CORRELATIVE SURFACES	[Shaded box from 100 to 10]				[Shaded box from 1000 to 100]				[Shaded box from 10 ⁴ to 10 ²]				[Shaded bar from WELL LOG to CORE AND OUTCROP]				
BEDSET	SEE TABLE TWO	[Shaded box from 10 to 1]				[Shaded box from 100 to 10]				[Shaded box from 10 ³ to 10 ¹]				[Shaded bar from WELL LOG to CORE AND OUTCROP]				
BED	SEE TABLE TWO	[Shaded box from 10 to 1]				[Shaded box from 100 to 10]				[Shaded box from 10 ³ to 10 ¹]				[Shaded bar from WELL LOG to CORE AND OUTCROP]				
LAMINA-SET	SEE TABLE TWO	[Shaded box from 10 to 1]				[Shaded box from 10 to 1]				[Shaded box from 10 ¹ to 10 ⁰]				[Shaded bar from CORE AND OUTCROP to CORE AND OUTCROP]				
LAMINA	SEE TABLE TWO	[Shaded box from 10 to 1]				[Shaded box from 10 to 1]				[Shaded box from 10 ¹ to 10 ⁰]				[Shaded bar from CORE AND OUTCROP to CORE AND OUTCROP]				

Figure 5. The Sequence Stratigraphy Hierarchy.

A stratigraphic hierarchy with the depositional sequence as the fundamental stratigraphic unit. Ranks are defined by intervals of geologic time, not by specific periodic processes (From Van Wagoner et al., 1990).

In his study of the Lower Jurassic in the High Atlas of Morocco, Crevello (1991) used subsidence and orbital forcing to explain the presence of sometimes hierarchic cyclicality in an ancient carbonate platform. This study examined the percentage of cyclicality for an entire carbonate platform and how it varied from the interior of the platform to the outer-slope. Crevello (1991) concluded that the outer-platform cyclic strata make up only 75% of the entire stratigraphic interval and that the inner-platform strata are less than 50% cyclic. According to Crevello (1991), this partial cyclicality is due in part to the interplay of subsidence and orbital forcing. Where cyclicality was recognized to be complete, Crevello (1991) concluded that it was due to orbital forcing mechanisms such as precession and eccentricity. Lack of cyclicality or incomplete cyclicality in some sections was attributed to variations in rates of subsidence. Based on these observations and conclusions, Crevello (1991) constructed a hierarchy for the outer-platform cycles which demonstrated a threefold superimposed cyclicality of 20:5:1. In addition, Crevello (1991) stated that this cycle ratio supports orbital forcing of high-frequency stacking patterns with periods of long eccentricity, short eccentricity and precession cycles which approximate rhythms of 360-400 k.y., 90-100 k.y. and 18-21 k.y., respectively. This study presented evidence for a process-determined hierarchy for the outer-platform where cyclicality was controlled by orbital forcing mechanisms, but did not show evidence for a process-determined hierarchy for the inner-platform cycles where subsidence was interpreted as the controlling mechanism. This study, like so many other studies (Elrick and Read, 1991; Busch and Rollins, 1984; Goldhammer et al., 1987, 1991; Osleger and Read, 1991) did not accept the concept that orbital forcing mechanisms are pervasive processes

producing cycles in all facies at all times. Similarly, most stratigraphers are reluctant to adopt a process-determined hierarchy based on these processes.

However, some researchers have utilized orbital forcing mechanisms to construct process-determined hierarchies of allocyclicity in the Milankovitch band. For example, in a recent study in the French Jura Mountains, Strasser (1994) recognized peritidal carbonates that displayed a hierarchic stacking of beds. Strasser (1994) recognized that one bed in most cases represents an elementary depositional sequence. Furthermore, these elementary sequences were bundled into groups of five, producing larger sequences, four of which formed even larger sequences (Strasser, 1994). This bundling and grouping of sequences produced a three-tiered hierarchy interpreted by Strasser (1994) as probably caused by orbital forcing mechanisms. The elementary sequences may correspond to the 20k.y. cycle of the precession of the equinoxes, and the two larger orders of sequences to the eccentricity with periods of 100 k.y. and 400 k.y. (Strasser, 1994).

Goodwin and Anderson (1992, 1993) have constructed a genetic hierarchy in which each of the ranks is connected to a specific periodic process. In this hierarchy the fundamental unit is the meter-scale allocycle or PAC (Fig. 6). Because of the high-frequency of this sixth-order allocycle it is assumed that it is controlled by the precessional signal (20 k.y. period). The fifth-order sequence, because of its lower frequency is assumed to be the result of short eccentricity (100 k.y. period). Therefore, a complete fifth-order sequence contains five sixth-order meter-scale allocycles or PACs. The orbital forcing mechanism responsible for the fourth-order sequence is long eccentricity (400 k.y. period). The complete

GENETIC HIERARCHY OF ALLOCYCLES

BANK	PERIOD	MECHANISM
2nd Order (Supersquence)	10 m. y. (?)	Tectono-eustasy (?)
3rd Order (Sequence)	2 m.y. (?)	Eccentricity (?)
4th Order	400 k.y.	Eccentricity
5th Order	100 k.y.	Eccentricity
6th Order (PAC)	20 k.y.	Precession

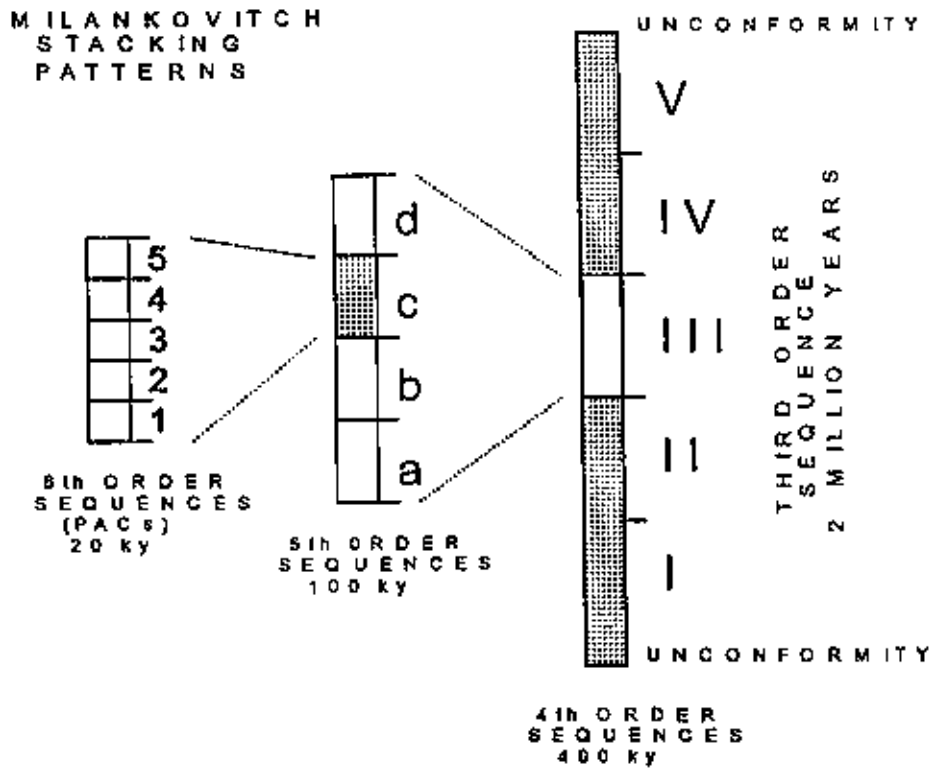


Figure 6. A Process-Determined Stratigraphic Hierarchy.

Each rank is defined by a specific process (Goodwin and Anderson, personal communication, 1992).

CHAPTER 3

CYCLICITY IN THE NEW CREEK AND CORRIGANVILLE FORMATIONS

Stratigraphic Setting

The Lower Devonian Helderberg Group of Pennsylvania crops out along a belt extending over 300 km in the Valley and Ridge Province, a region consisting of northeast-southwest plunging anticlines and synclines (Fig. 7). The specific interval chosen for this study consists of the New Creek and Corriganville Formations which comprise the basal portion of the third third-order sequence in the Helderberg Super Sequence (Anderson and Goodwin, 1993). The base of the study interval is bounded by an unconformity, first documented by Sullivan and Anderson (1986), separating the peritidal carbonates of the Keyser Formation from the open shelf facies of the New Creek Formation (Fig. 8). The New Creek Formation is overlain by the deeper-shelf facies of the Corriganville Formation which are in turn overlain by the basinal facies of the Mandata Formation (Fig. 8). The formation nomenclature utilized in this study and in other recent studies in this interval was established by Head (1969).

Dorobek and Read (1986) stated that the Helderberg Group consisted of three transgressive-regressive sequences, based on sedimentological and palentological criteria. In their interpretation the New Creek Formation formed as a result of the second major sea-level regression which allowed the New Creek to prograde over the underlying Keyser.

HELDERBERG OUTCROP BELT

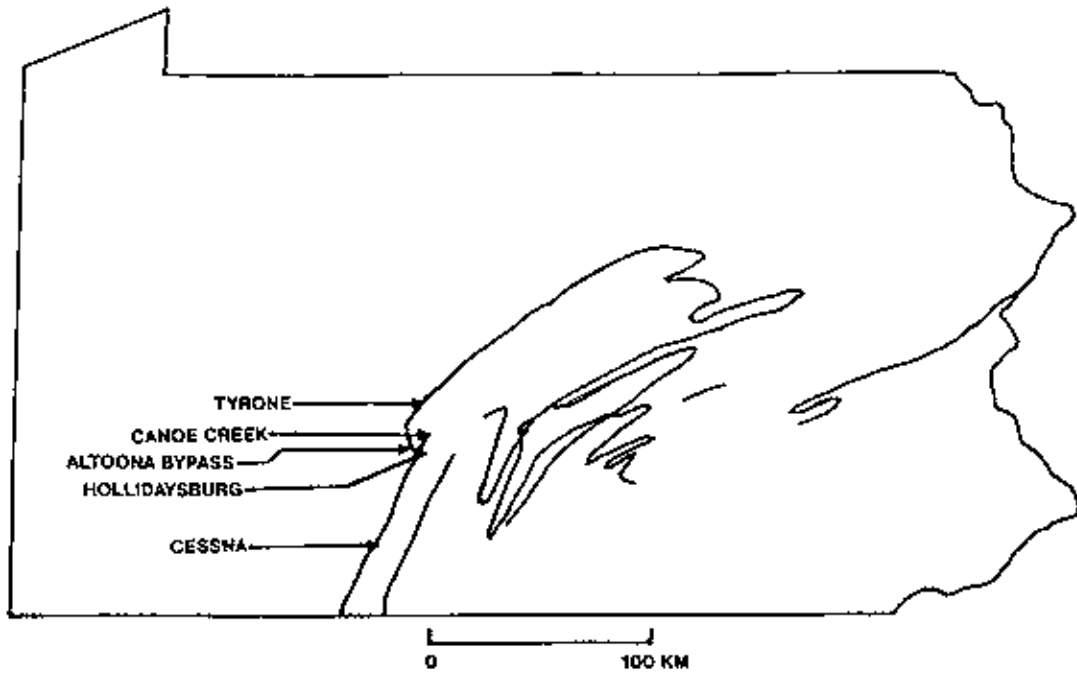


Figure 7. Lower Devonian Outcrop in Pennsylvania

Locations of outcrops studied and general distribution of Lower Devonian strata in Pennsylvania.

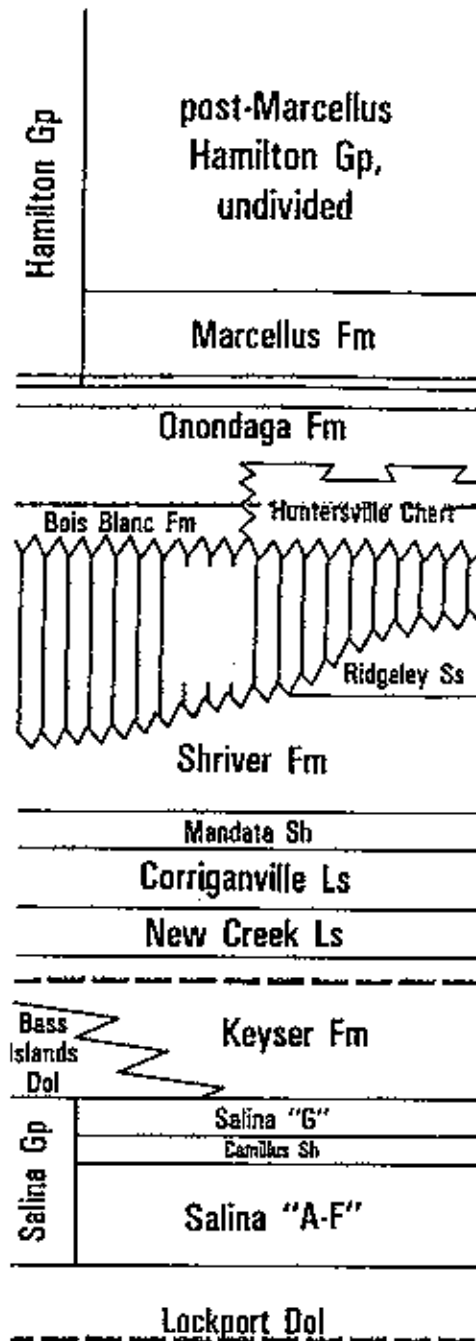


Figure 8. Generalized Stratigraphic Column, Central Appalachians (From Berg, 1983).

The final large-scale, basin-wide, gradual transgression caused the Corriganville to on-lap the New Creek (Dorobek and Read, 1986). This interpretation employs gradualistic assumptions to explain the vertical succession of the interval. These assumptions include laterally contemporaneous environments and migration of large-scale facies in response to gradual changes in base level. In contrast, application of the PAC model to this study interval will demonstrate that the New Creek and Corriganville Formations formed in response to episodic changes in sea level and not gradual changes in sea level as originally interpreted.

Sixth-Order Cycles (PACs)

Past work in the Helderberg Group of Pennsylvania has concentrated on the recognition, correlation and interpretation of PACs in the peritidal carbonates of the Keyser Formation (Goodmann ; Hamilton, 1986). The PAC model has been partially tested in shelf facies such as the New Creek and Corriganville Formations, but reliable criteria for recognizing PACs in these facies have not been established.

The most useful criteria for recognizing meter-scale allocycles in the New Creek and Corriganville Formations are: 1) textural changes, 2) change in bedding style, 3) the presence of chert, 4) sharp, laterally correlative bounding surfaces, and 5) sharp, correlative surfaces internal to PACs.

Textural changes in these facies are the most reliable indicators of a shallowing-upward motif. In general, PACs in these facies coarsen upward from fine-grained bioturbated calcarenite deposited in low-energy, possibly below wave base shelf environments. A coarse-textured rock is often the result of deposition in a high-energy environment near or above fair

weather wave base. In the Corriganville Formation, this textural difference is expressed as fine-grained (micrite and calcisiltite) basal (highstand) portions abruptly overlain by markedly coarser upper (lowstand) portion of the cycles. In the New Creek Formation, the textural variations are more subtle.

Changes in bedding style are still another indicator of shallowing. In some shelf environments bedding is present as a result of tempestite or turbidite deposition and in these deep-shelf environments the resulting rock texture is fine-grained (Aigner, 1982). In some shallow-shelf environments bedding can occur as the result of high energy deposition. Rocks resulting from this type of deposition are often coarse-grained and cross-bedded. The absence of bedding in shelf facies is due to bioturbation which indicates deposition in a deep environment, below fair weather wave base.

As previously discussed, stratigraphic surfaces are extremely important to PAC dynamics as they record an abrupt rise or fall in sea level. These surfaces are either sea-level-rise surfaces which bound PACs or are sea-level-fall surfaces internal to PACs (Fig. 1). As predicted by the PAC model, these surfaces are produced during times of non-deposition allowing for the concentration and preservation of phosphate and chert. In general there appears to be an association of chert with cycle boundaries in the New Creek and with the high-stand portion of the Corriganville sixth-order cycles.

New Creek Sixth-Order Cycles

The New Creek Formation, 8-10 feet thick throughout the study area, consists entirely of PACs. The contact between the underlying Keyser Formation and the New Creek is a

dramatic facies change from the laminated lime muds of the Keyser to the coarse-grained, gypidulid-bearing, crinoid-rich calcarenites of the New Creek (Fig. 8). This contact has been interpreted as an unconformity Sullivan and Anderson (1985) who demonstrated a progressive loss of PACs to erosion at the top of the Keyser Formation between the Cessna and Tyrone localities. The contact between the New Creek and the overlying Corriganville Formation is also a marked change from the calcarenitic facies of the New Creek to the shale-calcarenite couplets of the Corriganville Formation (Fig. 8). The surfaces that bound the New Creek are laterally extensive and therefore were allogically produced. Between the sequence boundaries are laterally extensive surfaces of discontinuity interpreted as PAC boundaries.

Without closely spaced localities to aid in detailed correlations, recognizing PACs in the New Creek sequence would be problematic because the facies changes are very subtle. In general, the basal PACs are massive, fossiliferous and chert-bearing. The upper PAC in the sequence tends to exhibit features characteristic of shallow subtidal environments, as it is more bedded. Reconnaissance work in the New Creek (Sullivan and Anderson, 1986), demonstrated the presence of two PACs in the sequence, but this study suggests the existence of three PACs at some localities.

Using a process-determined hierarchy, in the Milankovitch band, the ideal fifth-order sequence would contain five PACs. The absence of PACs 1 and 2 in the New Creek fifth-order sequence is explained by hiatus at the third-order Keyser-New Creek unconformity. Consequently, the numbering system for the New Creek begins with PAC 3.

PAC 3

The first New Creek PAC, PAC 3, at the Altoona Bypass locality is approximately 1 foot thick (Figs. 9 and 10). PAC 3 is a coarse-grained, gypidulid-bearing crinoid-rich calcarenite. The base of the cycle shows evidence of pre-New Creek erosion as it contains clasts of the underlying Keyser Formation. Texturally, PAC 3 is homogeneous, revealing no substantial indicators of shallowing; however, the presence of the sharp surface suggests a probable cycle boundary because of the disjunct facies observed at this horizon. The overlying facies is finer-grained and bioturbated. The same PAC, seven miles to the northeast at Canoe Creek (Fig. 11), is texturally and faunally identical to PAC 3 at Altoona Bypass.

PAC 3 at Tyrone (Fig. 12) approximately 12 miles to the north, is texturally and faunally identical to PAC 3 at other localities but is more than twice as thick (2.5 feet). The variation in thickness can be explained by a greater subsidence rate at Tyrone or irregular topography on the top of the Keyser. At Cessna, 40 miles to the south, PAC 3 is not present (Fig. 13) as a result of hiatus at the Keyser-New Creek unconformity. The rise in sea level that initiated the deposition of PAC 3 at the other localities did not inundate the Cessna region. Instead, the first PAC at Cessna correlates with PAC 4 at other localities in the study area.

PAC 4

Like PAC 3, PAC 4 consists of coarse-grained fossiliferous calcarenite. PAC 4 at Cessna, the most distal of all the Altoona area localities, is approximately 4 feet thick. The base of PAC 4 shows evidence of burrowing (Fig. 13) and the upper PAC boundary is marked

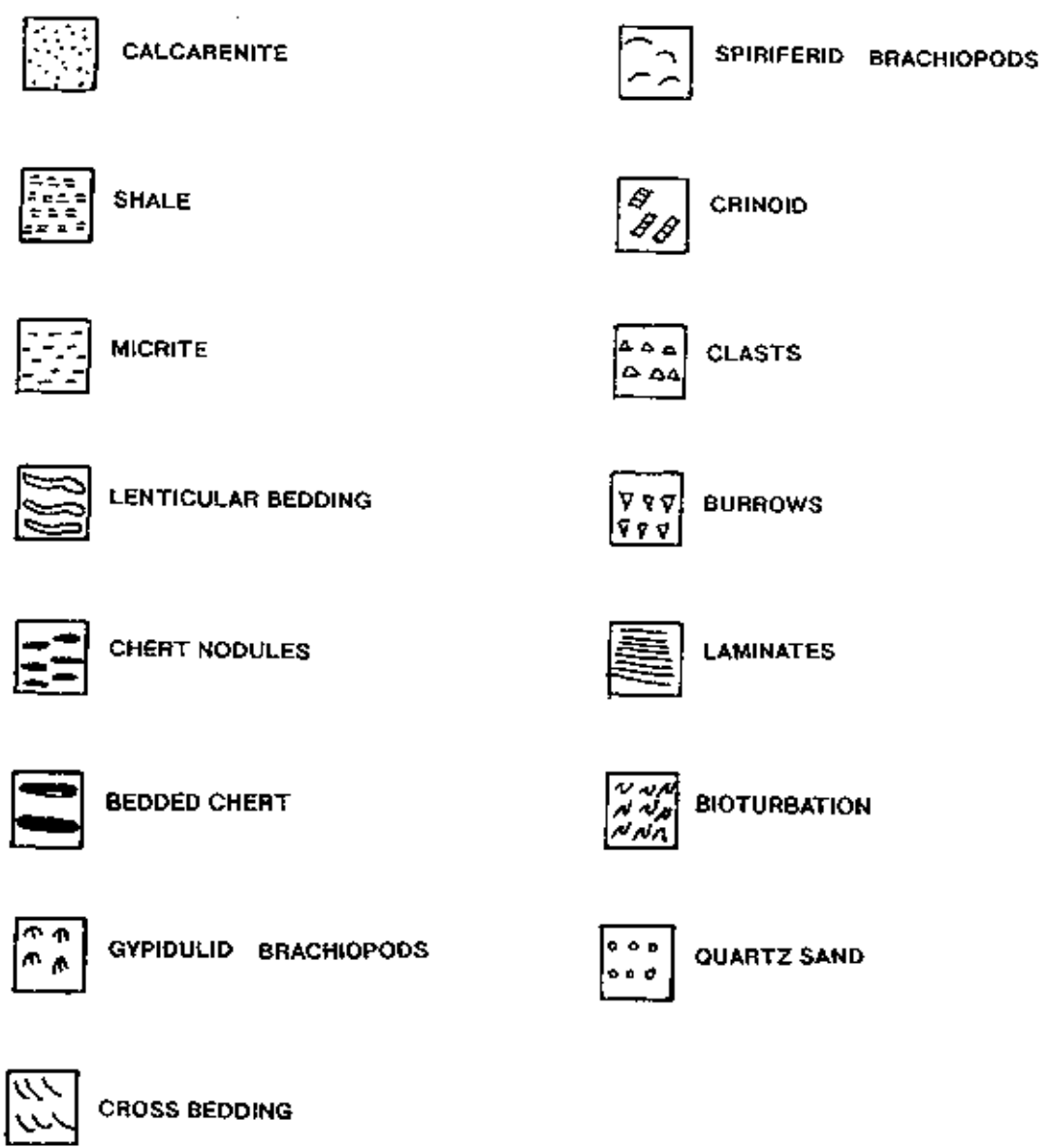


Figure 9. Symbols for Stratigraphic Columns.

ALTOONA BYPASS

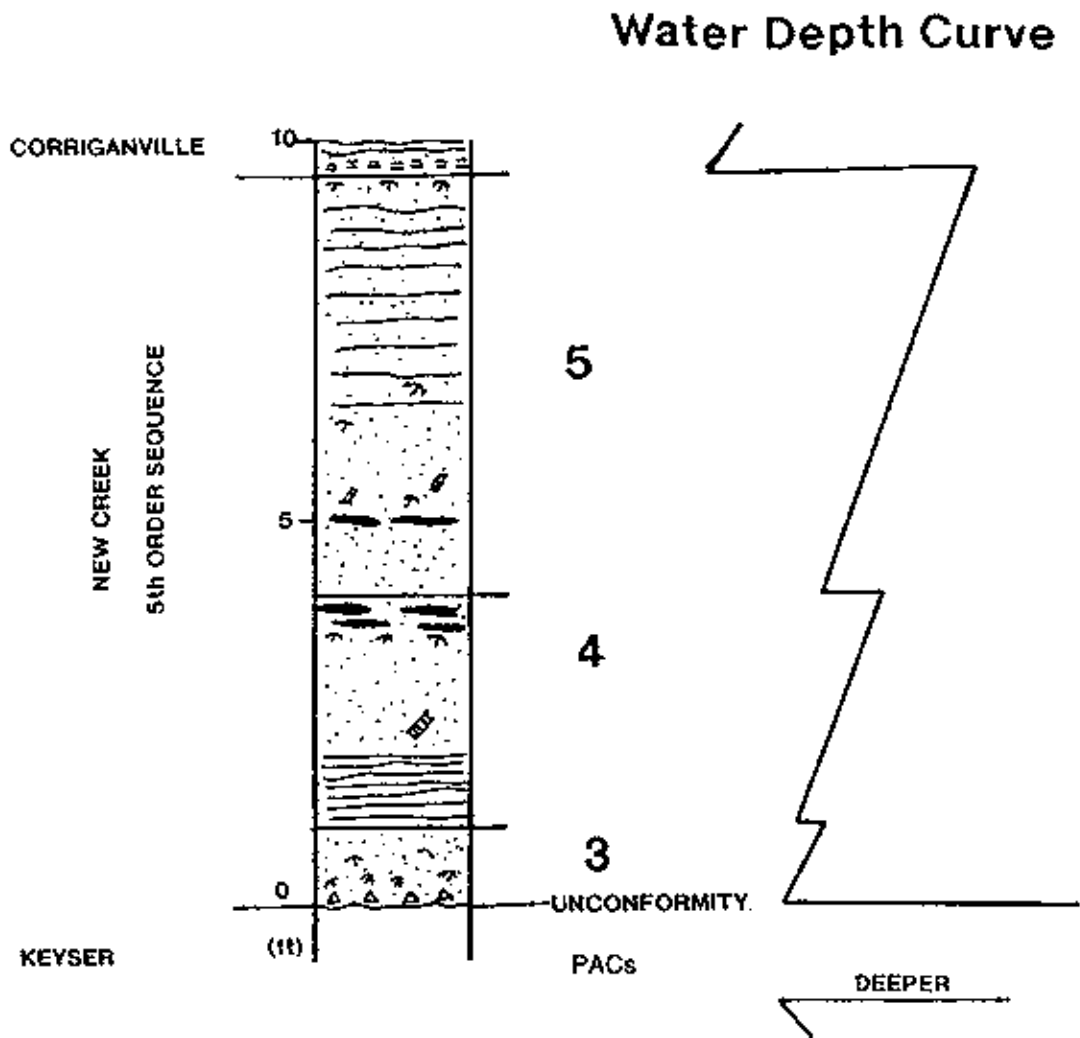


Figure 10. The New Creek Fifth-Order Sequence at Altoona Bypass.

CANOE CREEK

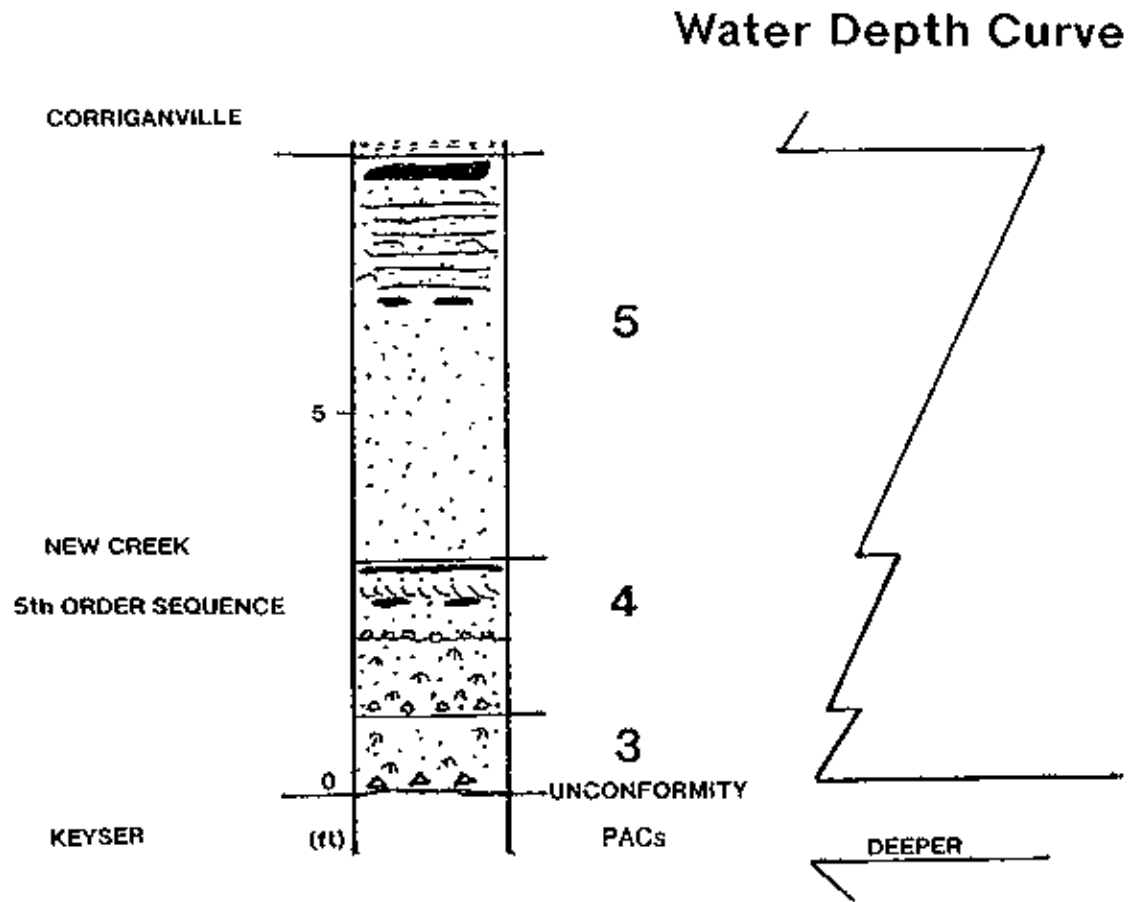


Figure 11. The New Creek Fifth-Order Sequence at Canoe Creek.

TYRONE

Water Depth Curve

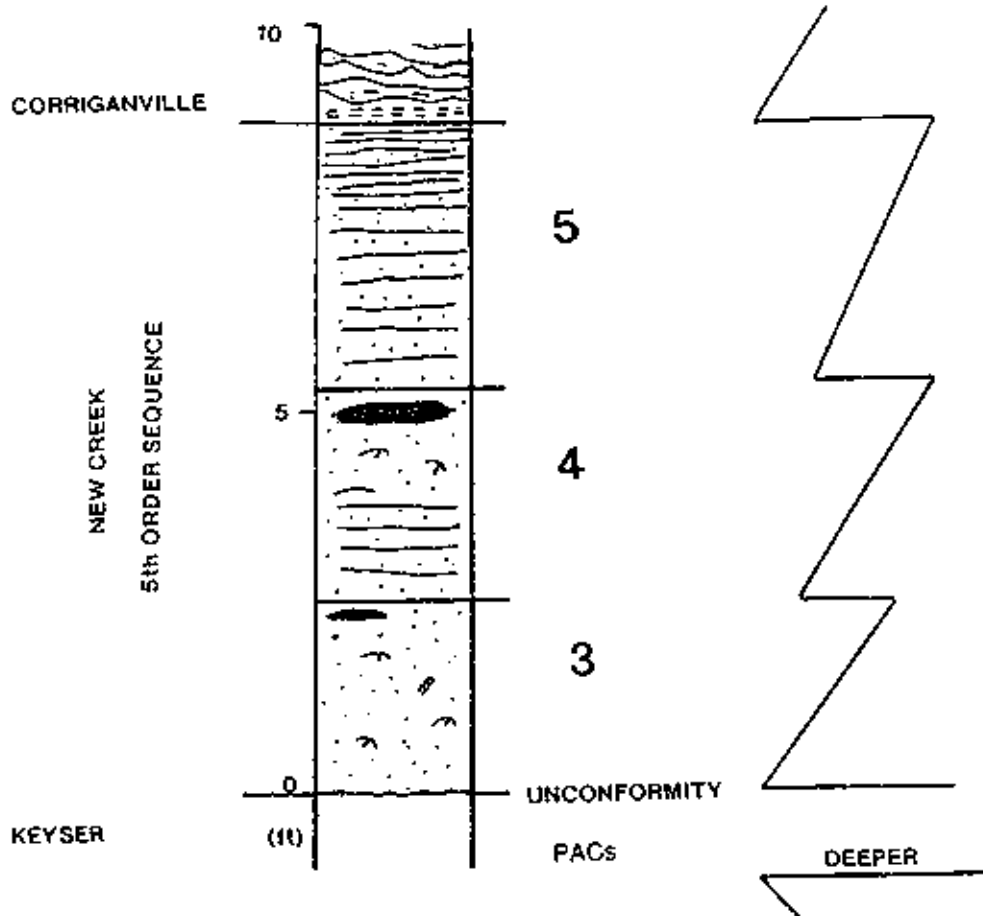


Figure 12. The New Creek Fifth-Order Sequence at Tyrone

by the presence of a 4 inch bedded chert, overlain by the finer-grained calcarenite of PAC 5. This relationship is laterally extensive at the same stratigraphic horizon throughout the study area. Preservation of the chert at this specific stratigraphic horizon is possibly explained by the PAC model. The PAC model predicts that a geologically instantaneous rise in sea level will produce a non-depositional surface. During a time of starved carbonate deposition, organic silica, possibly in the form of sponge spicules and radiolarians (Maliva and Siever, 1989), may have accumulated on this surface.

At Hollidaysburg, 25 miles north of Cessna, PAC 4 is 3 feet thick and is again capped by a prominent bedded chert. The same PAC at Canoe Creek, 5 miles north of Hollidaysburg, exhibits some subtle sedimentological variations (Fig. 11). Cycle thickness is consistent with the other localities and the chert occurs at the same horizon but the cycle contains a bed of cross-bedded quartz sandstone which represents the input of clastic sediments in a shallow near-shore paleoenvironment. Above the lower boundary of PAC 4 there is a concentration of gypidulid brachiopods in a discrete bed which may be the result of a storm surge.

PAC 5

PAC 5 at Hollidaysburg is similar in texture and faunal content to the other PACs in the New Creek sequence but the shallowing-upward motif is more pronounced (Fig. 14). The massive basal portion of the cycle is similar to the other three PACs in the sequence but the top of the cycle is more bedded. The cycle also contains thin beds of angular quartz sandstone and bedded chert. The identical PAC, 3 miles to the northwest, at Altoona Bypass exhibits a similar facies pattern (Fig. 10). The cycle is 5 and 1/4 feet thick, is massive at the

HOLLIDAYSBURG

Water Depth Curve

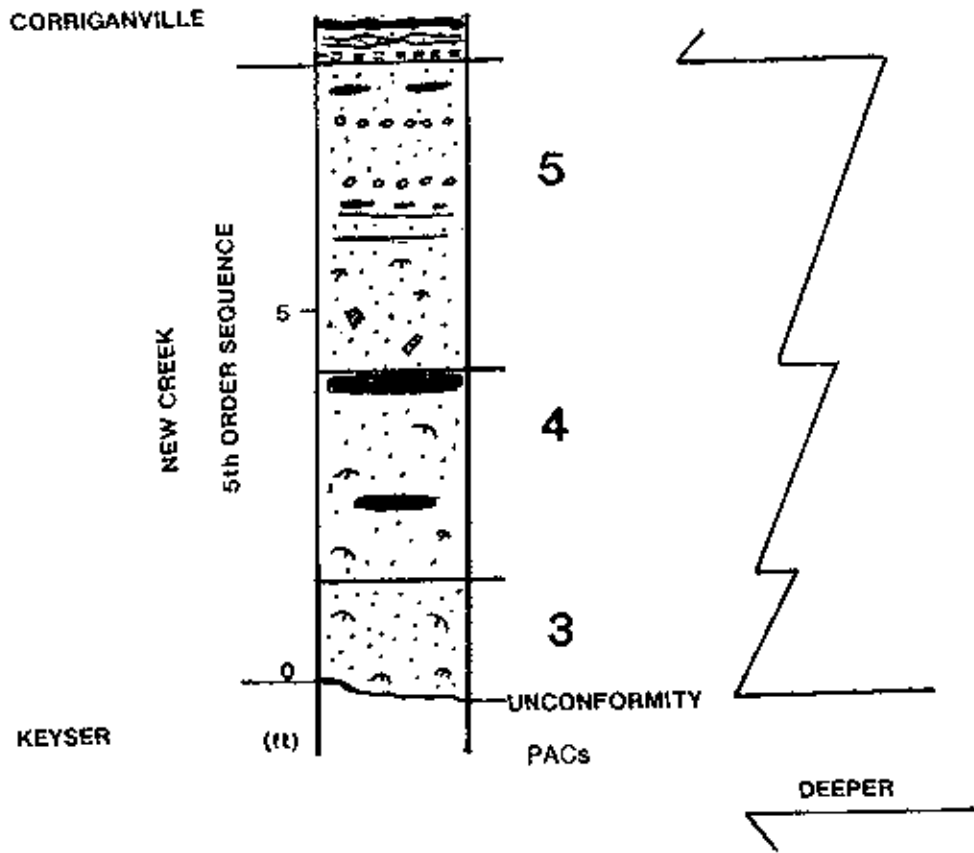


Figure 14. The New Creek Fifth-Order Sequence at Hollidaysburg.

base and progressively becomes more bedded toward the top. PAC 5 at Altoona Bypass is more bedded than its counterpart but does not contain quartz sand or an abundance of chert.

PAC 5

PAC 5 at Tyrone, 20 miles to the north, has some slight lateral variations, but this particular PAC is bedded throughout and is capped by cryptalgal laminites (Fig. 12), the shallowest facies in the New Creek. The laminites indicate an intertidal environment, suggesting that Tyrone is the most landward locality in the study area.

Using criteria established for recognizing allocycles in shallow-shelf facies, this study demonstrated that the New Creek Formation consists of meter-scale allocycles or PACs. Each cycle is bounded by laterally correlative surfaces of non-deposition which separate shallow facies at the top of the PAC from disjunctly deeper facies at the base of the overlying PAC. In addition each New Creek PAC exhibits a shallowing-upward motif. In PACs 3 and 4 this pattern was recognized by subtle changes in texture and in PAC 5 by the general increase in bedding towards the top of the cycle; though subtle, these features are found at all localities at the same stratigraphic levels.

Corriganville Sixth-Order Cycles

The Corriganville Formation is approximately 10-12 feet thick in the Altoona area and increases to 27 feet at Muncy, 270 miles to the northeast. The Corriganville sequence is completely divisible into sixth-order, meter-scale allocycles or PACs (Fig. 15). The contact between the underlying New Creek sequence and the Corriganville is a marked change from

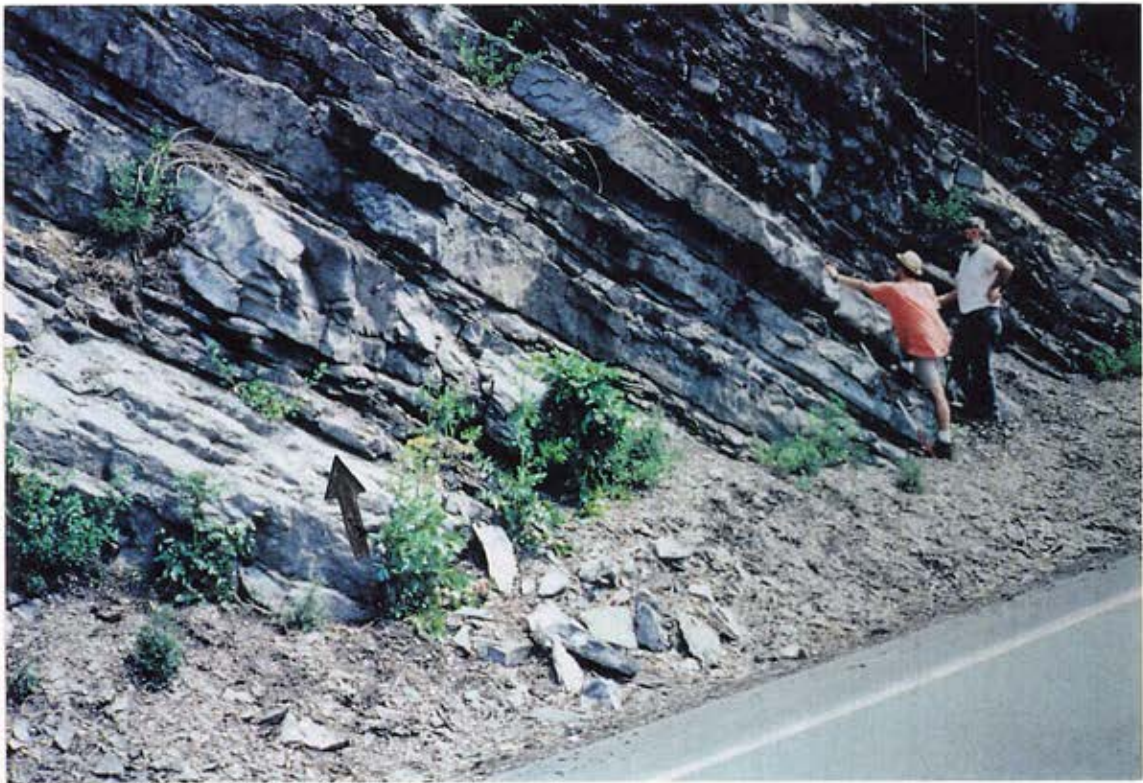


Figure 15. The Corriganville Fifth-Order Sequence at Hollidaysburg. The black arrow marks the contact between the New Creek and Corriganville Formations. The geologists are standing at the Corriganville-Mandata boundary.

the coarse-grained, gypidulid-bearing and crinoid-rich calcarenites of the New Creek to the shale-calcarenite couplets of the Corriganville (Fig. 8). The contact between the Corriganville and the overlying Mandata Formation is a dramatic change from the deep shelf facies of the Corriganville to the basinal black shale facies of the Mandata (Fig. 8). The sharp surfaces which bound the Corriganville sequence are laterally extensive and therefore allogenically produced. Internal to the sequence are surfaces of discontinuity marking disjunct facies relationships; these sixth-order boundaries are correlative. Sixth-order cyclic patterns in the Corriganville sequence are more pronounced than in the New Creek. Building on criteria established by Side (1987) for work in similar facies, modified criteria were developed for the Corriganville. The most useful criteria for recognizing PACs in the Corriganville include: 1) textural changes; 2) sharp surfaces internal to PACs; 3) the presence of volcanic ash deposits; 4) the presence of chert; and 5) sharp bounding surfaces. Reconnaissance work in the Corriganville by Sullivan and Anderson (1986) demonstrated the presence of 4 PACs in the sequence but this study suggests the existence of 5 PACs at most of the localities.

The PACs which comprise the Corriganville sequence have a unique and easily recognizable motif. The basal portion of each PAC is dominated by shale and bioturbated micritic limestone which is abruptly overlain by a massive fossiliferous calcarenite. The basal micritic shaley portion of each Corriganville PAC was deposited during the highstand of eustatic sea level (Fig. 1). The massive fossiliferous calcarenite was deposited during the lowstand of eustatic sea level (Fig. 1). The sharp surface or discontinuity which separates the highstand from the lowstand is interpreted as a sea-level-fall surface (Touchberry et al., 1991). These surfaces and patterns of facies are laterally extensive (Fig. 16).



Figure 16. *Corriganville PACs 4 and 5 at Hollidaysburg*

The hammer head is resting on the PAC 3-4 boundary. The black arrow is pointing to the sea-level-fall surface which separates the basal highstand unit from the upper lowstand unit. The black line defines the boundary between PACs 4 and 5.

PAC 1

In general PAC 1 is approximately 1 foot thick throughout the study area and exhibits the characteristic highstand-lowstand motif. PAC 1 at Hollidaysburg is less than 1 foot thick and marks an abrupt facies change from the massive fossiliferous calcarenites of the underlying New Creek sequence to the shale-limestone couplets of the Corriganville (Fig. 17). PAC 1 contains a basal shale (highstand) and an upper bioturbated, chert-bearing calcarenite (lowstand) separated by a sea-level-fall surface (S.L.F). There is also a bentonite at the base of the PAC. Preservation of the volcanic ash at this specific stratigraphic horizon is explained by the PAC model (Anderson and Goodwin, 1991).

The PAC model predicts that a surface of non-deposition will be produced by a rapid rise in sea level. During this time of starved deposition, volcanic ash would be concentrated above the surface because no carbonate or clay was being deposited. The ash would later undergo diagenesis to form bentonite.

PAC 1, 5 miles to the north at Canoe Creek, is texturally and structurally identical to its counterpart at Hollidaysburg. This one-foot-thick PAC contains a distinct highstand and lowstand portion separated by a S.L.F surface (Fig. 18). However, there is no chert or bentonite at the New Creek-Corriganville boundary. Either the volcanic ash was eroded after deposition or was never deposited.

At Tyrone the absence of PAC 1 can be explained through reconstruction of paleogeography. The top PAC in the New Creek at Tyrone consists of peritidal laminates, suggesting the presence of a topographic high (Fig. 19). Conceivably, the sea level rise which

HOLLIDAYSBURG

Water Depth Curve

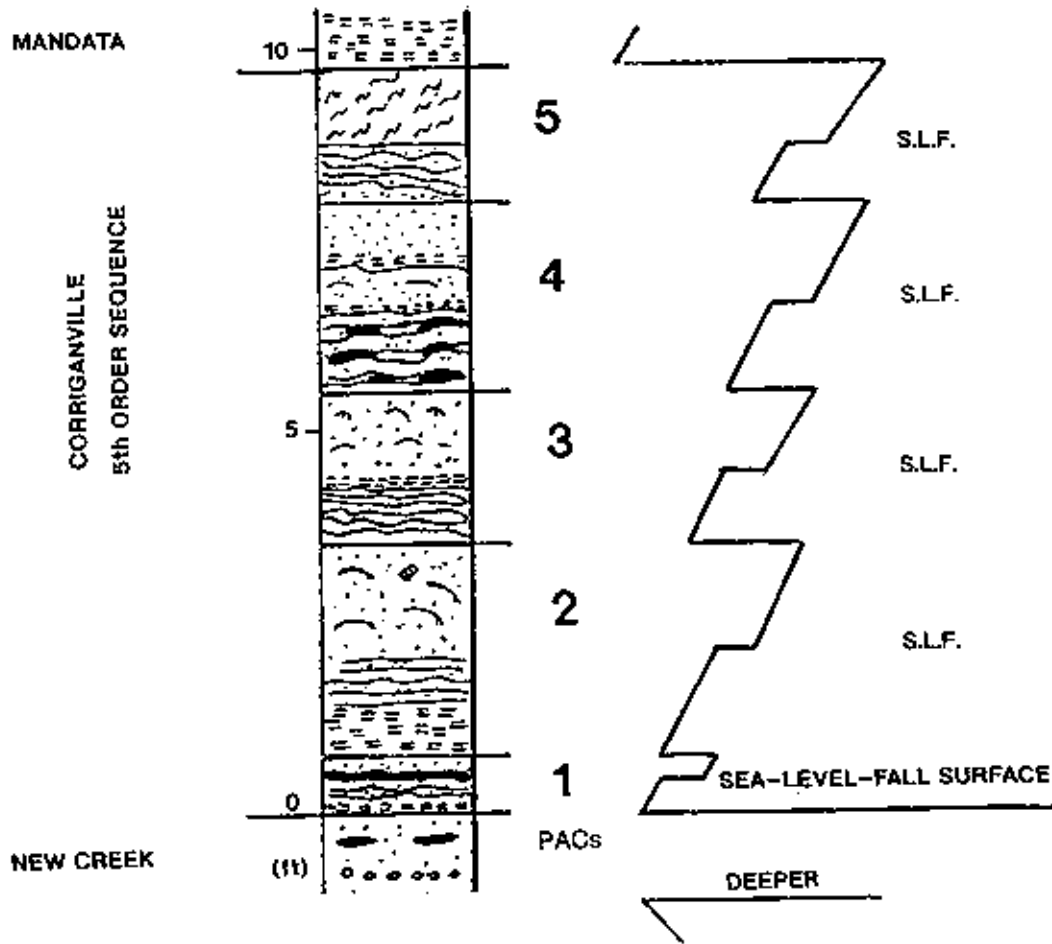


Figure 17. The Corriganville Fifth-Order Sequence at Hollidaysburg.

CANOE CREEK

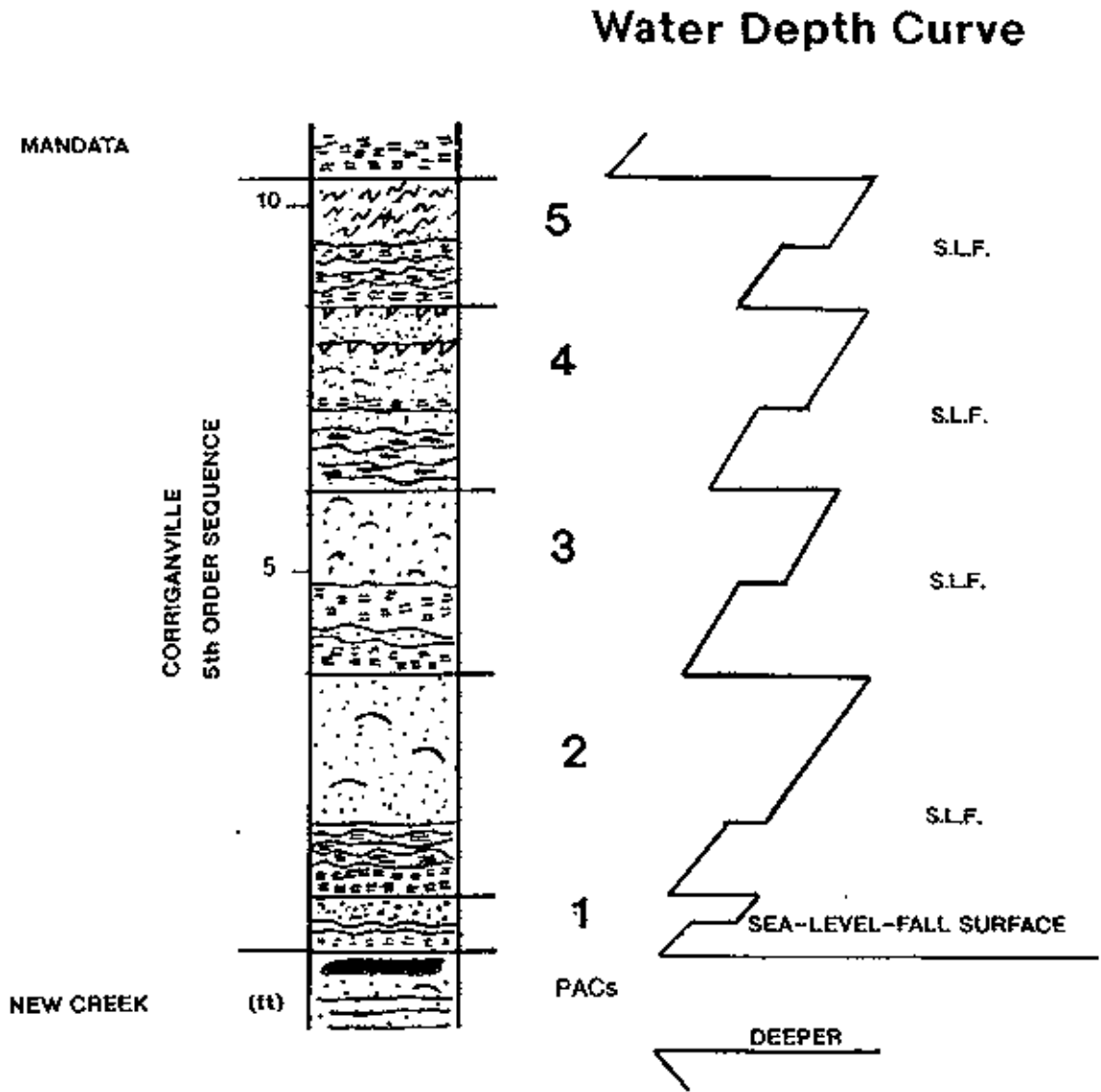


Figure 18. The Corriganville Fifth-Order Sequence at Canoe Creek.

TYRONE

Water Depth Curve

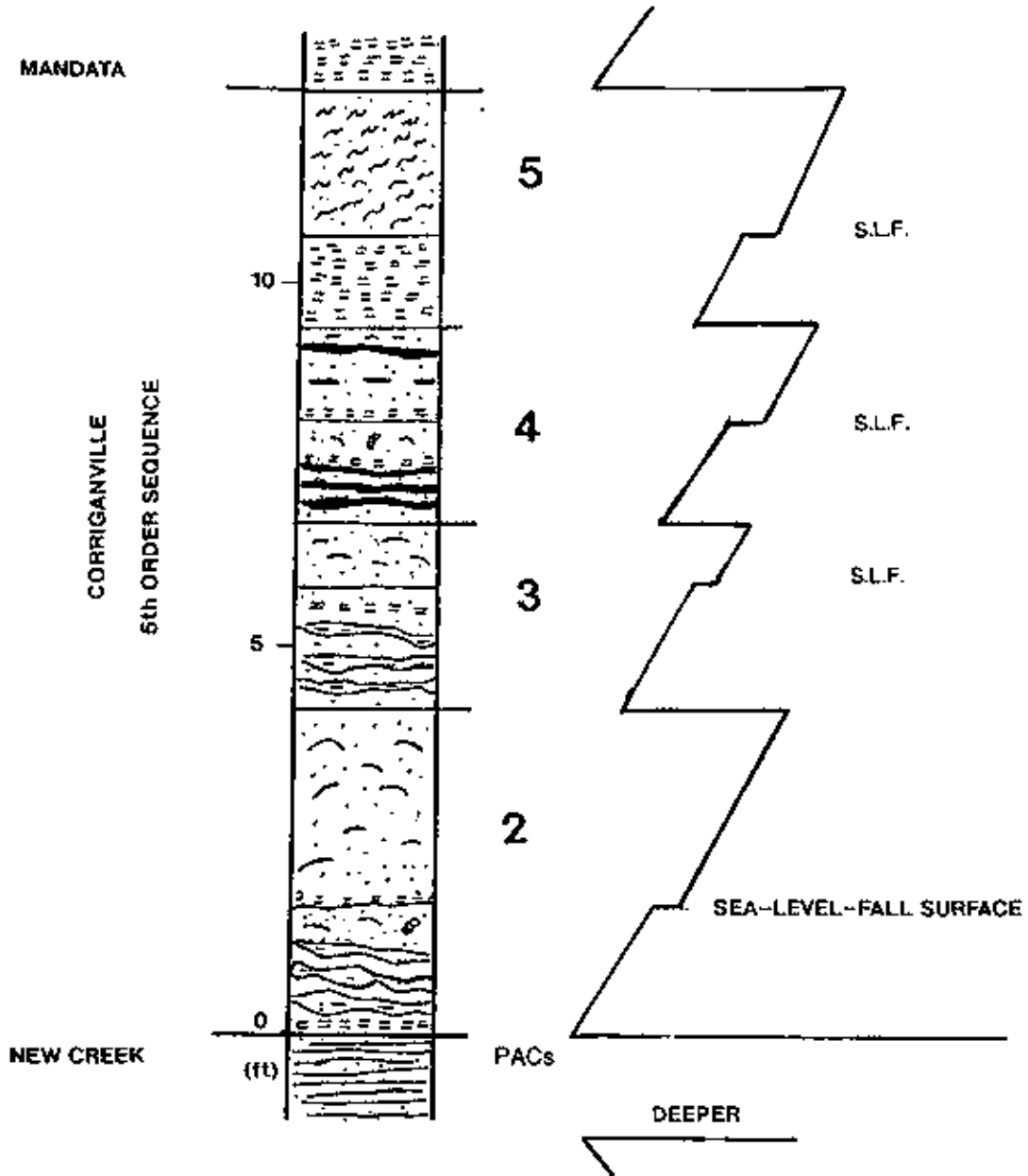


Figure 19. The Corriganville Fifth-Order Sequence at Tyrone.

initiated the deposition of PAC 1 in other areas of the basin was not of great enough magnitude to flood the topographically high area at Tyrone. initiated the deposition of PAC 1 in other areas of the basin was not of great enough magnitude to flood the topographically high area at Tyrone.

PAC 2

PAC 2 is approximately 2 feet thick throughout the study area and contains both the highstand and lowstand components. At Hollidaysburg this cycle is approximately 2.5 feet thick and contains a distinct basal highstand unit and upper lowstand unit separated by a S.L.F. surface (Fig. 17). The highstand unit is predominantly non-fossiliferous shale which grades up into thin wavy limestone beds. The lowstand portion of PAC 2 is a massive limestone which contains spiriferid brachiopods, crinoids and other fossil debris. The equivalent PAC at Canoe Creek, 5 miles to the north, is 2 feet thick and displays the characteristic highstand-lowstand motif (Fig. 18). Internal to the highstand unit are lenticular limestone beds which are frequently laminated at their tops, suggesting that they were once parts of continuous tempestites or turbidites. At Tyrone, 15 miles to the northwest, the lenticular structures internal to the highstand unit do not contain these laminations. At this locality however, PAC 2 does exhibit the characteristic highstand-lowstand motif but the cycle has doubled in thickness (Fig. 19). The increase in cycle thickness is proportionate in the highstand and lowstand facies. Similar increases in cycle thickness of the other PACs within the sequence were not observed.

PAC 3

PAC 3 throughout the study area displays the characteristic highstand-lowstand motif and is approximately 2 feet in thickness. This cycle at Tyrone contains an uncharacteristically thick highstand unit consisting of shale and lenticular micrite (Fig. 19). The lowstand unit contains spiriferid and gypidulid brachiopods. The occurrence of the gypidulid brachiopods is significant because these brachiopods suggest a return to New Creek shallow-shelf facies, the shallowest facies observed in the Corriganville sequence thus far. PAC 3 at Canoe Creek is similar to PAC 3 at Tyrone as it contains gypidulid brachiopods in the lowstand unit (Figs. 18, 20). Cycle thickness is approximately 2 and 1/4 feet thick, equally divided between the highstand and lowstand units of the PAC. However, the highstand unit consists predominantly of shale with only a single bed of competent micrite. This facies pattern is also present at Hollidaysburg, 5 miles to the south (Fig. 21), and at Cessna, 20 miles farther south (Fig. 22).

PAC 4

This PAC, also 2 feet thick throughout the study area, displays the characteristic highstand-lowstand motif. At Cessna, the highstand unit of PAC 4 has the characteristic micritic texture, minor amounts of shale and a significant increase in the amount of chert. Faunally the highstand unit contains spiriferid brachiopods and other fossil debris. The lowstand unit is composed of two distinct beds separated by a sharp surface. These two distinct units internal to the lowstand portion of PAC 4 are laterally extensive because at Hollidaysburg 20 miles to the north, the lowstand unit consists of two distinct portions

separated by a sharp surface (Fig. 17). The highstand unit is dominated by shale and beds of lenticular micrite which have undergone diagenesis to form chert; there is no evidence of fossils. As at other localities, PAC 4 at Canoe Creek displays similar characteristics which include a cherty lenticular highstand unit and a lowstand portion with two distinct units (Fig. 18). The sharp surface which separates the two portions of the lowstand unit shows evidence of horizontal burrowing. Conditions which promote horizontal burrowing prevail at times of non-deposition which can only occur at a S.L.F. surfaces or at PAC boundaries, in subtidal environments. Therefore, there is evidence to potentially subdivide PAC 4 into two cycles. However, this division is not warranted without further correlation and a re-evaluation of the Corriganville interval.

PAC 5

PAC 5 throughout the study area is 2 feet thick and exhibits the characteristic highstand-lowstand structure. At Canoe Creek, the highstand unit consists of a combination of shale and lenticular lime mud with no fossil debris (Fig. 18). The lowstand unit is a heavily bioturbated calcarenite. The top of the cycle has a high concentration of phosphatic debris (Smith and Berkheiser, 1992). This phosphatic zone occurs at the same stratigraphic horizon throughout the study area and is probably associated with non-deposition during the major deepening event which initiated deposition of the Mandata Shale. PAC 5 exhibits the consistent highstand-lowstand motif at all localities in the study area.

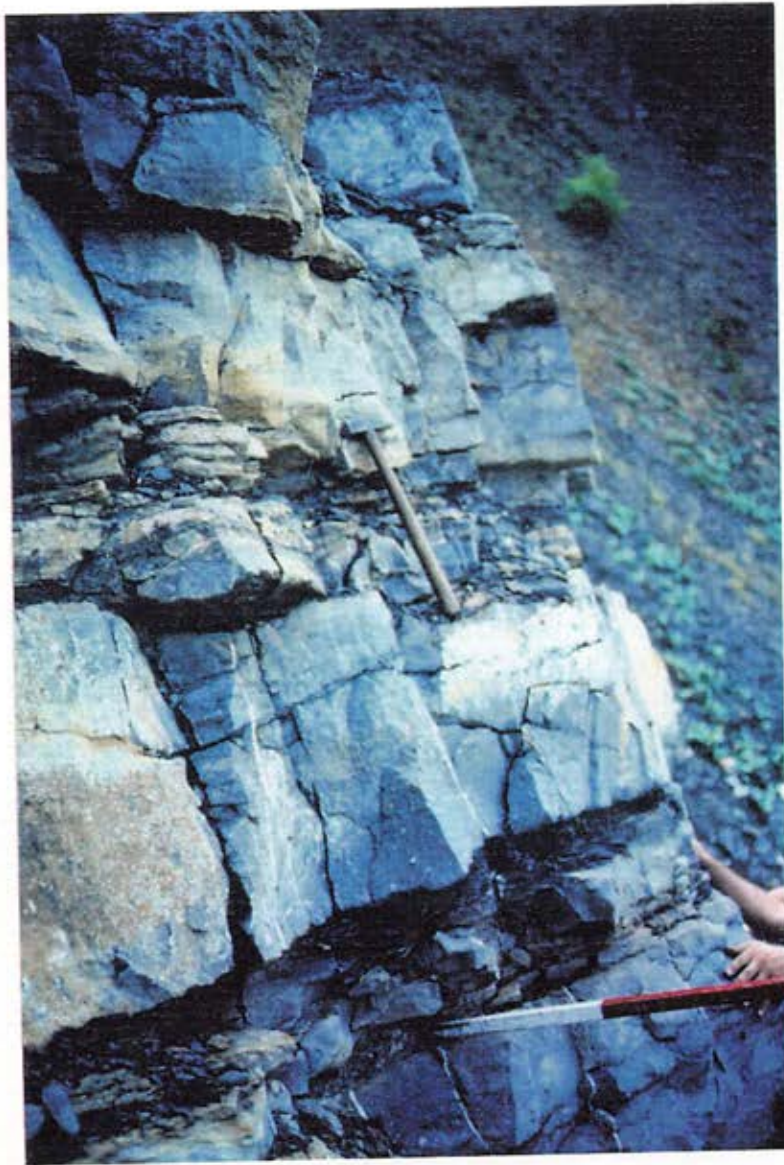


Figure 20. PACs 3 and 4 at Canoe Creek.

The PAC stick is pointing to the contact between PAC 2 and PAC 3. The hammer is embracing the highstand portion of PAC 4.



Figure 21. PAC 3 at Hollidaysburg.

The lower PAC stick marks the contact between PAC 2 and PAC 3. The upper PAC stick is at the contact between PAC 3 and PAC 4.

CESSNA

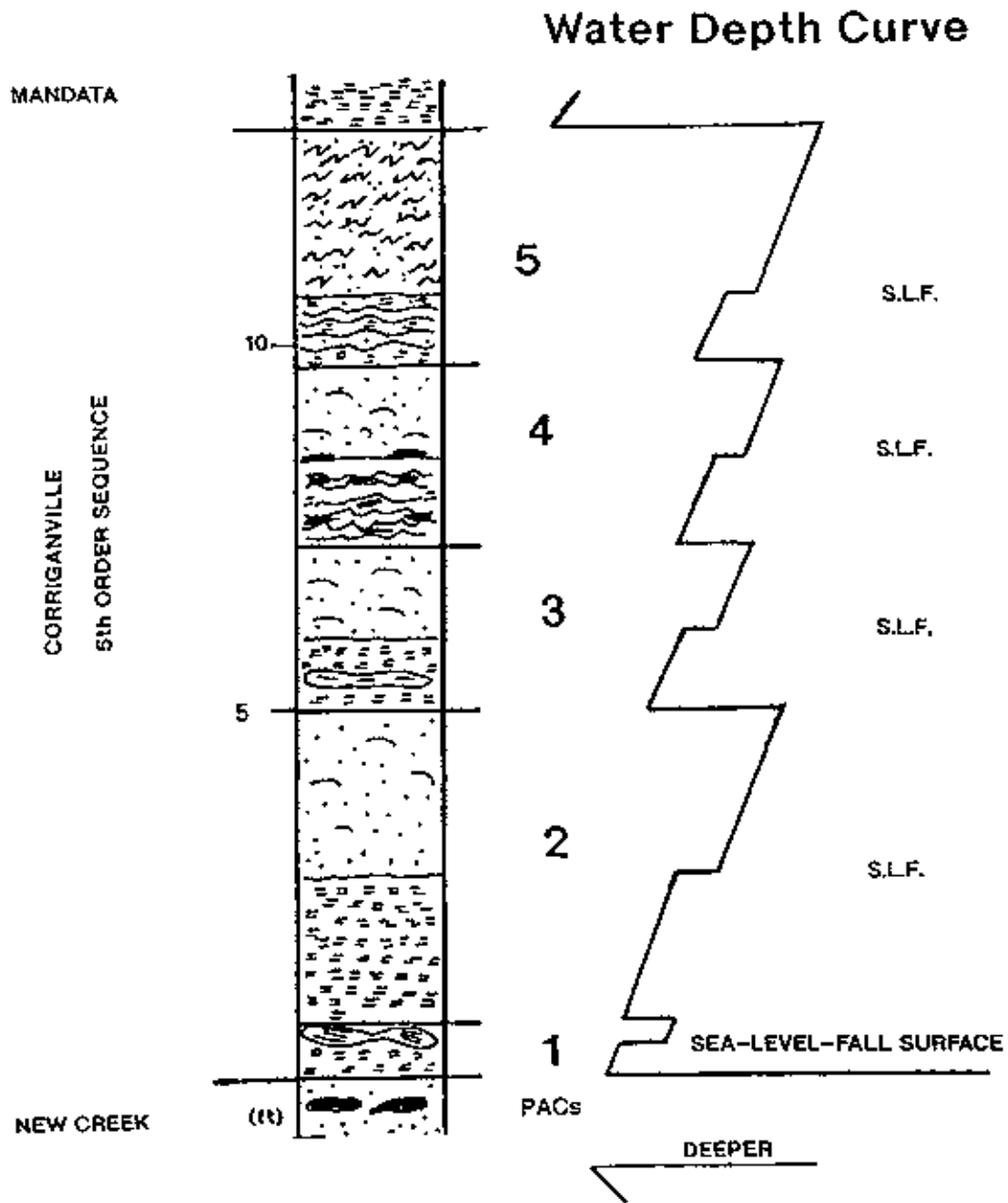


Figure 22. The Corriganville Fifth-Order Sequence at Cessna.

Fifth-Order Sequences

As predicted by the PAC model and demonstrated by this study, the New Creek and Corriganville Formations consist entirely of sixth-order, meter-scale allocycles or PACs. In addition to the sixth-order, precession-driven cyclicality, the stacking patterns of these sixth-order cycles provides evidence for the fifth-order, short-term, eccentricity-modulated cyclicality (Fig. 23). At each formation boundary there is a major facies change and within each formation there is a progressive shallowing-upward trend, as the cycles at the base of each sequence contain deeper facies than those observed near the top of each sequence. These observations are interpreted as the precessional signal being enhanced by eccentricity at the formation boundary, producing the large degree of facies change and damped by eccentricity during the remainder of the sequence, producing the overall shallowing pattern of each formation.

New Creek Fifth-Order Sequence

The New Creek Formation has been interpreted as a fifth-order sequence because of the large degree of facies change observed at the Keyser-New Creek contact. In addition this boundary has also been documented as an unconformity and a third-order sequence boundary (Goodwin and Anderson, 1992). The degree of facies change observed at the New Creek-Corriganville boundary is also too great in magnitude to be a simple 20 k.y. precessional boundary. Consequently it is interpreted that the surfaces which bound the New Creek Formation are the result of the precessional signal which has been enhanced by eccentricity.

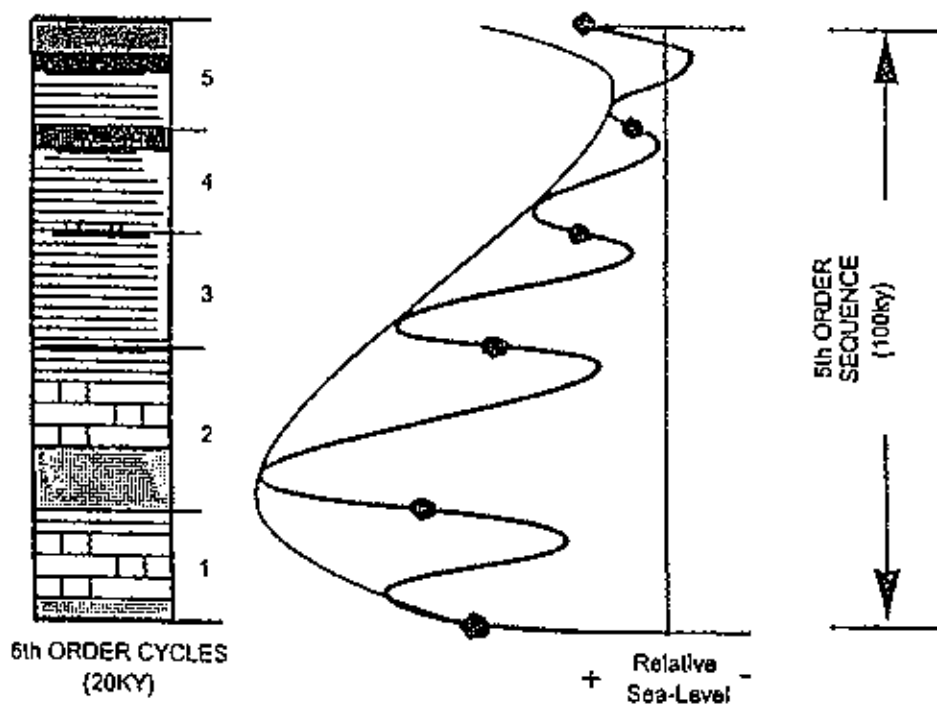


Figure 23. Eustasy in the 100 k.y. Eccentricity Signal.

Diagram of an ideal fifth-order sequence, with all sixth-order cycles present, and a relative sea-level curve showing eustasy throughout one eccentricity signal. Note that sixth-order boundaries occur at inflection points of precessional sea-level rises (From Chadwick, 1994).

The basal two PACs in the New Creek sequence at Hollidaysburg consist of massive fossiliferous calcarenite, deposited in a shallow shelf environment (Fig. 14). PAC 5 is also fossiliferous calcarenite but becomes progressively more bedded towards the top of the cycle. The bedded nature of PAC 5 indicates that it was deposited in a shallower more restricted environment than the underlying PACs. The New Creek sequence at Tyrone, 15 miles to the north, exhibits the same large-scale, allogenicly produced facies patterns observed at Hollidaysburg. The basal PACs 2 and 3 at Tyrone are massive, fossiliferous, shallow shelf calcarenites (Fig. 12). PAC 5 at Tyrone is similar to PAC 5 at Hollidaysburg as it progressively becomes more bedded toward the top of the cycle, shallowing to laminates in the top 2 feet. The facies represented by the top of PAC 5 indicate an intertidal environment. This large-scale allogenicly produced shallowing-upward facies pattern which is prevalent in the New Creek sequence has a scale and duration comparable to fifth-order sequences described in other intervals (Smith and Anderson, 1992; Chadwick and Goodwin, 1993; Mairello and Ketterer, 1993) .

Goodwin and Anderson (1992) predict that the fundamental unit in the genetic hierarchy of allocycles is the sixth order meter-scale allocycle or PAC, produced by the precessional orbital cycle which has a period of approximately 20 k.y. (Fig. 23). The fifth-order sequence is produced by the orbital eccentricity cycle which has a duration of 100 k.y. The ideal fifth-order sequence should therefore contain five sixth-order allocycles or PACs. The New Creek is an incomplete fifth order sequence in the study area because it contains only two or three sixth-order allocycles or PACs. Presumably, the basal PACs in the New

Creek, PACs 1, 2 and at some localities PAC 3, were never deposited due to hiatus at the third-order unconformity between the Keyser and the New Creek.

Corriganville Fifth-Order Sequence

The effects of eccentricity on precession have also been observed in the Corriganville sequence. These patterns are similar to those observed in the New Creek, including a marked degree of facies change at sequence boundaries and an overall shallowing trend. PACs at the base of the Corriganville exhibit deeper facies than those at the top of the sequence.

PAC 1 at Hollidaysburg contains no fossils and is very thin and PAC 2 is thicker and contains a more diversified fauna. In PAC 3 the presence of gypidulid brachiopods signifies the return to New Creek facies and PAC 5 shows evidence of extreme bioturbation (Fig. 17). This pattern is also apparent at Canoe Creek where, PAC 4 contains horizontal burrows (Fig. 18). In general, the basal PACs have thick highstand units with more shale and fine-grained lowstand units. In the upper PACs, the highstand units are not as thick, contain less shale and are more silicified. The lowstand units are more coarse-grained. These shallowing-upward patterns are laterally extensive throughout the study area suggesting an allogenic control, specifically the eccentricity signal.

As predicted by the genetic hierarchy of allocycles (Goodwin and Anderson, 1992), the ideal fifth-order sequence should contain five sixth-order allocycles which is true for most localities (Fig. 23). The Corriganville Formation at Hollidaysburg contains five sixth-order allocycles or PACs which exhibit an overall shallowing trend (Fig. 17). This is also the case at Canoe Creek and Altoona Bypass which are localities within 5 miles of one another (Fig.

18). However, at Tyrone, 10 miles to the northeast, the Corriganville sequence contains only 4 PACs; the basal PAC 1 is missing (Figs. 19, 24). As suggested by the presence of cryptalgal laminites at the top of the New Creek at this locality, Tyrone may have existed as land during the time represented by Corriganville PAC 1. Therefore, the Corriganville is an incomplete fifth-order sequence at Tyrone and is a complete fifth-order sequence at the other localities. As predicted by the Milankovitch model (Fig. 23) the second cycle within this sequence contains the deepest facies at all localities.



Figure 24. The Corriganville Fifth-Order Sequence at Tyrone.

The bedding-parallel PAC stick marks the New Creek- Corriganville contact. The geologist is pointing to the contact between PACs 2 and 3.

CHAPTER 4

SUMMARY AND CONCLUSIONS

This study demonstrates that the New Creek and Corriganville Formations consist entirely of sixth-order, meter-scale allocycles or PACs. Stacking patterns of PACs in the two formations are consistent with predictions of the Milankovitch Theory of orbital forcing of high-frequency sea-level fluctuations. Precession, with a periodicity of approximately 20 k.y., was responsible for the formation of sixth-order cycles and their boundaries. Short eccentricity (100 k.y.) served as a modulator of the precessional signal, producing major facies change at fifth-order boundaries (e.g. New Creek-Corriganville contact) and a general shallowing trend within each formational fifth-order sequence.

The incomplete New Creek fifth-order sequence consists of two or three sixth-order meter-scale allocycles. The basal sequence boundary is a marked facies change from the peritidal carbonates of the underlying Keyser Formation to the shallow-shelf facies of the New Creek at a third-order unconformity. The upper boundary of this fifth-order sequence, the New Creek-Corriganville contact, is an eccentricity-enhanced precessional boundary as indicated by the major facies change at that horizon. The shallowest facies in the New Creek are the top in PAC 5 which displays intertidal facies at Tyrone.

The Corriganville fifth-order sequence consists of five sixth-order PACs at each locality except Tyrone. Each PAC is characterized by distinct highstand and lowstand portions separated by a sea-level-fall surface. As in the New Creek sequence the shallowest facies occur at the top of the Corriganville.

Recognition of these cyclic patterns, at the sixth and fifth-order scale, supports the genetic hierarchy constructed by Goodwin and Anderson (1992, 1993). This study has demonstrated that the sixth-order precession-driven cyclicity is bundled into fifth-order eccentricity-modulated cycles. These stacking patterns are laterally correlative throughout the study area and therefore provide evidence for orbital forcing mechanisms in shelf facies.

The relationship of the New Creek and Corriganville fifth-order sequences to large-scale allocyclicity will remain problematic until correlations with the Helderberg Group in New York State are confirmed. At this stage Goodwin and Anderson (1991, 1993) have established a third-order sequence boundary at the Keyser-New Creek contact; the same unconformity forms the Manlius-Coeymans contact in the Hudson Valley. It is conceivable that the New Creek-Corriganville interval is an incomplete fourth-order sequence in the study area; two fifth-order sequences are probably missing at the Keyser-New Creek unconformable third-order boundary. The upper fourth-order boundary (Corriganville-Mandata contact) appears to be conformable throughout the study area, as there is no evidence of missing cycles. Reconnaissance work to the south and northeast also supports these observations. Complete sub-division of this third-order sequence into fourth-order sequences will require detailed study of the New Creek to Oriskany interval throughout the Appalachian Basin.

REFERENCES CITED

- Aigner, T., 1982, Calcareous tempestites: storm-dominated stratification in the Upper Muschelkalk Limestone (Middle Trias, SW Germany), in Einsele, G., and Seilacher, A., eds., *Cyclic and Event Stratification*. Springer-Verlag, New York, Heidelberg, Berlin, 526 p.
- Anderson, E.J. and Goodwin, P. W., 1990, The significance of metre-scale cycles in the quest for a fundamental stratigraphic unit: *Journal of Geological Society, London*, v. 147, p. 507-518.
- Anderson, E.J. and Goodwin, P. W., 1992a, What distinguishes PACs from parasequences: *Geological Society of America Abstracts with Programs*, v. 24, no. 3, p. 3.
- Anderson, E.J. and Goodwin, P. W., 1992b, The primacy of the precessional signal: *Geological Society of America Abstracts with Programs*, v. 24, p. A110.
- Anderson, E.J., Goodwin, P. W. and Sobieski, T. H., 1984, Episodic accumulation and the origin of formation boundaries in the Helderberg Group of New York State: *Geology*, v. 12, p. 120-123.
- Berg, T.M., McInery, M.K., Way, J.H. and MacLachlan, D.B., 1983, *Stratigraphic Correlation Chart of Pennsylvania*, General Geology Report No. 75, Topographic and Geologic Survey of Pennsylvania.
- Berger, A., 1988, Milankovitch theory and climate: *Reviews of Geophysics*, v. 26, no. 4, p. 624-657.
- Bond, G.C., Kominz, M.A., and Beavan, J., 1991, Evidence for orbital forcing of Middle Cambrian peritidal cycles: Wah Wah Range, south-central, in Franseen, E.K., et al., eds., *Sedimentary Modeling: Computer simulations and methods for improved parameter definition*: *Kansas Geological Survey Bulletin*, v. 233, p. 239-318.
- Brett, C.E., and Baird, G.C., 1986, Symmetrical and upward shallowing cycles in the Middle Devonian of New York State and their implications for the Punctuated Aggradational Cycle Hypothesis: in: M.A. Arthur and R.E. Garrison, eds., *Milankovitch Cycles Through Time*. *Paleoceanography*, v. 1, p. 431-446.
- Busch, R. G. and Rollins, H. B., 1984, Correlation of carboniferous strata using the hierarchy of transgressive-regressive units: *Geology*, v. p. 471-474.

- Chadwick, W. J. and Goodwin, P. W., 1993, Allocycle symmetry, in the hierarchic structure of the Upper Silurian Tonoloway Formation: Geological Society of America Abstracts with Programs, v. 25, no. 2, p. 8.
- Chadwick, W.J., 1994, Correlation of Milankovitch-band cyclicity in the peritidal carbonates of the Tonoloway Formation, Central Pennsylvania and Western Maryland: M.A. Temple University, 69 p.
- Crevello, P. D., 1991, High-frequency carbonate cycles and stacking patterns: Interplay of orbital forcing and subsidence on Lower Jurassic rift platforms, High Atlas, Morocco, in Franseen, E.K., et al., eds., *Sedimentary Modeling: Computer simulations and methods for improved parameter definition*: Kansas Geological Survey Bulletin, v. 233, p. 207-230.
- Dorobek, S.L. and Read, J.F., 1986, Sedimentology and Basin Evolution of the Siluro-Devonian Helderberg Group, Central Appalachians, *Journal of Sedimentary Petrology*, v. 56, p. 601-613.
- Elrick, M. And Read, J.F., 1991, Cyclic ramp-to-basin carbonate deposits, Lower Mississippian, Wyoming and Montana: A combined field and computer modeling study, *Journal of Sedimentary Petrology*, v. 61, p. 1194-1224.
- Fischer, A. G., 1964, The Lofer cyclothems of the Alpine Triassic: *Kansas Geological Survey Bulletin*, v. 169, p. 107-149.
- Fischer, A. G. and Bottjer, D. J., 1991, Orbital Forcing and sedimentary sequences: *Journal of Sedimentary Petrology*, v. 61, p. 1063-1069.
- Fischer, A.G., Herbert, T.D., Napoleone, G., Silvia, I.P. and Ripepe, M., 1991, Albian pelagic rhythms (Piobbico core), *Journal of Sedimentary Petrology*, v. 61, p. 1164-1172.
- Goldhammer, R.K., Dunn, P.A. and Hardie, L.A., 1987, High Frequency Glacio-eustatic Sea-level Oscillations with Milankovitch Characteristics recorded in Middle Triassic Platform Carbonates in Northern Italy, *Amer. Jour. Science*, v. 287, p. 853-892.
- Goldhammer, R. K., Oswald, E. J. and Dunn, P. A., 1991, Hierarchy of stratigraphic forcing: example from middle Pennsylvanian shelf carbonates of the Paradox Basin: *Kansas Geological Survey Bulletin*, v. 233, p. 362-413.
- Goodman, P.T., 1986, Punctuated aggradational cycles and their stratigraphic implications in the Upper Silurian-Lower Devonian carbonate sequence (Tonoloway and Keyser Formations) in central Pennsylvania: M.A., Temple University, 81 p.

- Goodwin, P.W. and Mauriello, D.J., 1994, Orbital forcing of a hierarchy of carbonate allocycles: Devonian Cedar Valley Group, Iowa: Geological Society of America Northeast Section Meeting Abstracts with Programs, v. 26 no. 5. P. 17
- Goodwin, P.W. and Anderson, E.J., 1993, Paleogeographic reconstruction of time slices within an allocyclic stratigraphic hierarchy: Society of Economic Paleontologists and Mineralogists Abstract with Programs, p. 50.
- Goodwin, P.W., Anderson, E.J., Orzechowski, C. and Smith, L.B., 1992, Late Silurian-Early Devonian Milankovitch stacking patterns: the case for a process-determined hierarchy of allocycles: North Central Geological Society of America Abstracts with Programs, v. 24, no. 4, p 16.
- Goodwin, P.W. and Anderson, E.J., 1988, Episodic development of Helderbergian paleogeography New York State Appalachian Basin: *in* McMillan, N.J., Embry, A. F. And Glass, D.J., eds. Devonian of the World. Second International Symposium on the Devonian System, Canadian Society of Petroleum Geologists, p. 553-568.
- Goodwin, P.W., Anderson, E.J., Goodman, W.M. and Saraka, L. J., 1986, Punctuated aggradational cycles: implications for stratigraphic analysis. *in* Arthur, M.A. and Garrison, R.E., eds. Milankovitch Cycles through Time. Paleooceanography, 1. P. 417-429.
- Goodwin, P. W. and Anderson, E. J., 1985, Punctuated aggradational cycles: a general hypothesis of episodic stratigraphic accumulation: Journal of Geology, v. 93, no. 5, p. 515-533.
- Goodwin, P. W. and Anderson, E. J., 1992, The case for a process-determined hierarchy of allocycles: Geological Society of America Abstracts with Programs, v. 24, p. A110.
- Hamilton, F. K., 1988, Anatomy of a single punctuated aggradational cycle, Keyser formation, Silurian-Devonian, Central Pennsylvania: M.A., Temple University, 86 p.
- Head, J.W., 1969, An Integrated Model of Carbonate Depositional Basin Evolution: Late Cayugan (Upper Silurian) and the Helderbergian (Lower Devonian) of the Central Appalachians: Ph. D. dissertation, Brown University, 390 p.
- Koerschner, W.F. and Read, J.F., 1990, Field and modeling studies of Cambrian carbonate cycles, Virginia Appalachians-Reply, Journal of Sedimentary Petrology, v. 60, p. 795-796.

- Koerschner, W.F. and Read, J.F., 1989, Field and modeling studies of cambrian carbonate cycles, Virginia Appalachians: *Journal of Sedimentary Petrography*, v. 5, p.573-588.
- Laporte, L.F., 1967, Carbonate deposition near mean sea-level and resultant facies mosaic: Manlius Formation (Lower Devonian) of New York State: *American Association of Petroleum Geologists Bulletin*. v. 51, p. 73-101.
- _____, 1969, Recognition of a transgressive carbonate sequence within an epeiric sea Helderberg Group (Lower Devonian) of New York State, *in* Friedman, G.M., ed. *Depositional Environments in Carbonate Rocks: Special Publication of the Society of Economic Paleontologists and Mineralogists* 14, p. 98-101.
- Maliva, R.G., and Siever, R., 1989, Chertification histories of some late Mesozoic and Middle Devonian platform carbonates: *Sedimentology*, v. 36, p. 907-926.
- Mauriello, D. J. and Ketterer, M. W., 1993, Correlation of hierarchal Upper Silurian stacking patterns generated by Milankovitch orbital forcing: *Geological Society of America Abstracts with Programs*, v. 25, no. 2, p. 73.
- Orzechowski, C., Eckel, S. K. and Goodwin, P. W., 1992, Evidence of Early Devonian Milankovitch forcing: *Geological Society of America Abstracts with Programs*, v. 24, no. 3, p. 67.
- Osleger, D. and Read, J. F., 1991, Relation of eustasy to stacking patterns of meter-scale carbonate cycles, Late Cambrian, U. S. A.: *Journal of Sedimentary Petrology*, v. 106, no. 7, p. 1225-1252.
- Read, J. F. and Goldhammer, A. K., 1988, Use of Fischer plots to define 3rd order sea-level curves in peritidal carbonates, Early Ordovician, Appalachians: *Geology*, v. 16, p. 895-899.
- Rickard, L.V., 1962, Late Cayugan (Upper Silurian) and Helderbergian (Lower Devonian) stratigraphy in New York: *New York State Museum and Science Service Bulletin* 386.
- Shelton, S.D. and Anderson, E.J., 1993, Eccentricity and precession forced cyclicality in the Upper Silurian Williamsport Sandstone member of the Wills Creek Formation: *Geological Society of America Abstracts with Programs*, v. 25, no. 2, p. 78.
- Side, D.M., 1987, *Stratigraphic Analysis of the Lower New Scotland Formation: An Episodic Perspective*: M. A., Temple University, 75 p.
- Sloss, L.L., 1963, Sequences in cratonic interior of North America: *Geological Society of America Bulletin*, v. 74, p. 93-114.